PB82-114539

NATO-CCMS Pilot Study on Disposal of Hazardous Wastes: Chemical, Physical, and Biological Treatment of Hazardous Wastes in NATO Countries

Project Leader: United States

NATO Committee on the Challenges of
Modern Society, Brussels (Belgium)

9 Mar 81

U.S. Department of Commerce
National Technical Information Service
NTIS

BIBLIOGRAPHIC INFORMATION

PB82-114539

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PERFORMER: NATO Committee on the Challenges of Modern
Society, Brussels (Belgium).
NATO/CCMS-119

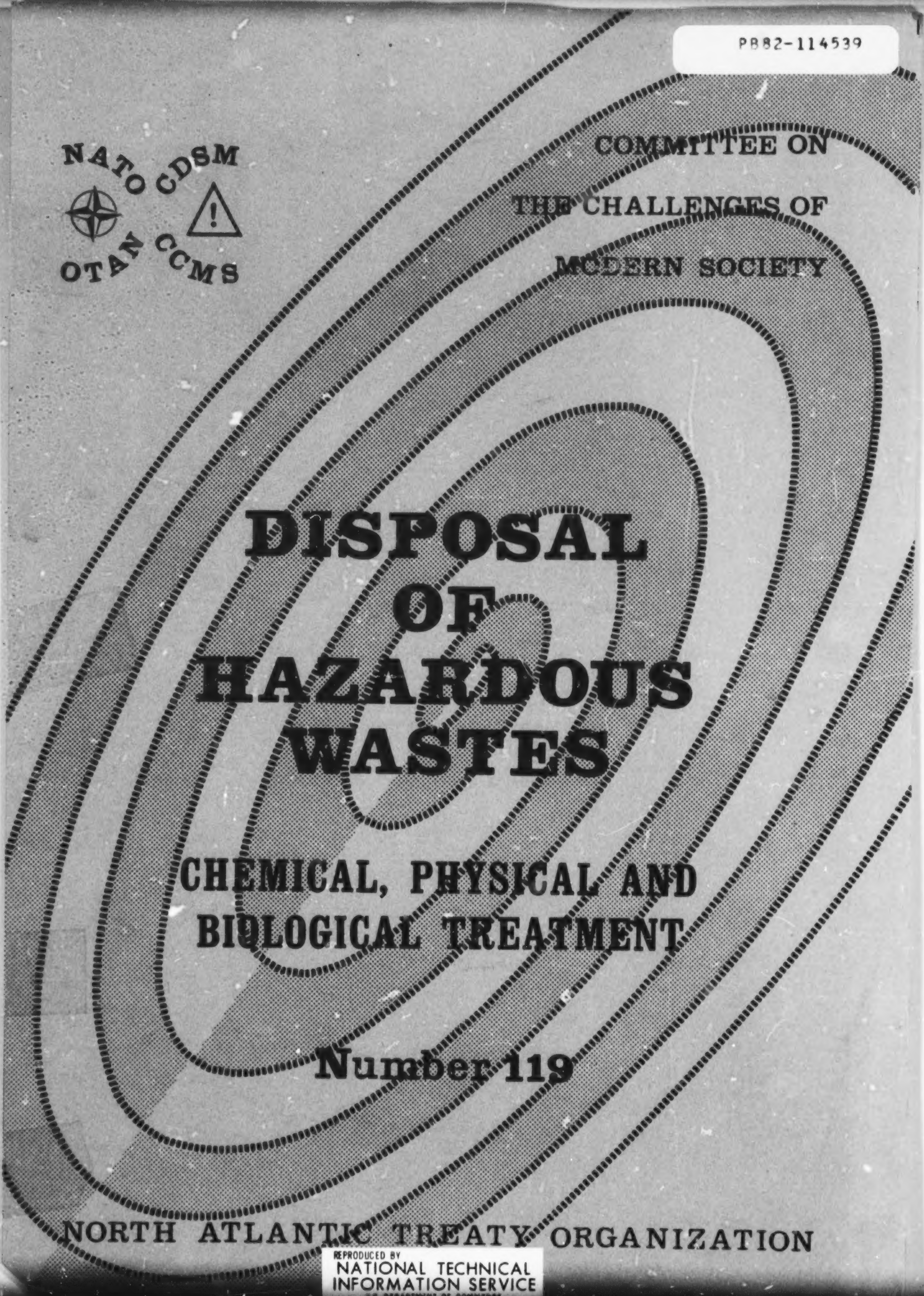
Report is result of efforts of members of The North Atlantic Treaty Organization's CCMS Pilot Study on Disposal of Hazardous Wastes to assemble information on the state-of-the-art of technology for chemical, physical and biological treatment of hazardous industrial waste in their respective countries.

KEYWORDS: *Hazardous materials, *Solid waste disposal, *Foreign technology, *Chemical treatment, *Physical treatment, *Biological industrial waste treatment.

Available from the National Technical Information Service,
Springfield, Va. 22161

PRICE CODE: PC A07/MF A01

PB82-114539



NATO CDSM
OTAN CCMS

COMMITTEE ON
THE CHALLENGES OF
MODERN SOCIETY

DISPOSAL OF HAZARDOUS WASTES

CHEMICAL, PHYSICAL AND BIOLOGICAL TREATMENT

Number 119

NORTH ATLANTIC TREATY ORGANIZATION

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE

Chemical, Physical, and Biological Treatment of Hazardous Wastes in NATO Countries

NATO-CCMS Pilot Study
on
Disposal of Hazardous Wastes

FINAL REPORT

Project Leader
United States

March 9, 1981

This report is printed on recycled paper

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1.0 INTRODUCTION

1.1 AIMS OF THE PROJECT

This report is the result of the efforts of the members of the North Atlantic Treaty Organization Committee for Challenges to Modern Society (NATO/CCMS) Pilot Study on Disposal of Hazardous Wastes to assemble information on the state-of-the-art of technology for chemical, physical, and biological treatment of hazardous industrial waste in their respective countries. This effort is directed at making the member countries and waste generators aware of the alternatives to land disposal and incineration for management of industrial wastes.

1.2 CONTENTS OF THE REPORT

The following sections appear in this report.

- Hazardous waste management policy which affects chemical, physical, and biological treatment applications in each country.
- Identification of waste types and treatment processes applicable to these wastes including a process/waste matrix to quickly identify treatment methods for wastes.
- A discussion of the future potential for recovery of hazardous wastes in each country.
- A discussion of the centralized treatment of wastes in each country.
- Current research and development efforts in each country.
- Conclusions and recommendations of the study.

1.3 METHOD

The following countries particpated in the project: Belgium, Canada, Federal Republic of Germany, France, Netherlands, Norway, Portugal, Turkey, United Kingdom, and the United States of America. The United States served as project leader. All of the countries listed participated in project meetings, and the Federal Republic of Germany, France, Netherlands, United Kingdom, and the United States submitted written contributions.

1.4 SCOPE AND LIMITATION

This report does not contain a comprehensive list of all of the applications of chemical, physical, and biological treatment processes to hazardous waste, or of the wastes themselves. The potential number is too great to be included in any single report or series of reports. The whole hazardous waste management field is currently in a state of flux, with evolving regulatory programs in many member countries impacting potential applications. This report instead will serve as a source of ideas for both the countries which have advanced hazardous waste programs and for those which are now beginning to recognize the problem and desire to do something about it.

2.0 HAZARDOUS WASTE MANAGEMENT POLICY

The NATO countries are at different stages in developing hazardous waste management policies. Also, due to variations in topography, geology, and types of industries, each country is approaching its program from a different point of view.

Several programs are presented below. They all have the same prime thrust to protect human health and the environment, while avoiding unreasonable economic impacts.

2.1 FEDERAL REPUBLIC OF GERMANY

These principles of the 1972 Waste Disposal Act and the 1975 Waste Management Program of the Federal Republic of Germany govern the country's waste disposal policy:

- The production of waste should be reduced as far as is possible and economically feasible;
- Wastes should be reused or recycled unless not economically feasible;
- Only wastes that cannot be economically reused shall be disposed of and then without causing any damage to the environment; and
- Harmful wastes must not be disposed of if they are amenable to treatment.

Economics are of particular importance. Selection of the appropriate method for disposing of wastes must consider costs, risks, and benefits of the disposal methods potentially acceptable for a particular waste. Certain wastes are assigned to specific disposal/treatment methods according to conditions set in the the license granted to a disposal/treatment facility. The license lists the wastes that can be accepted by the facility. Where appropriate, the license may require specific pretreatment processes for some wastes. However, specific treatment processes are not always assigned to specific wastes because of the variation among facilities.

Biological processes are not used for the disposal of dangerous wastes in the Federal Republic. They are used, however, in recycling organic material. Enzymatic fermentation processes are used for the extraction of alcohol from wastes from the potato, fruit, and diary industries. Processes for the extraction of protein feedstuffs from cellulose-bearing residues are being developed. These residues, however, are not considered wastes in the Federal Republic. The discharge of dangerous effluents into sewage treatment plants or waters for the purpose of "biological treatment" is considered sewage treatment, not waste treatment, in the Federal Republic.

Finally, there is a link between the disposal methods used and the disposal policies in the different Federal States. A State operating a State-wide company with a broad range of chemical and physical treatments, including incineration, tends [illegible] xclude many types of wastes from co-disposal at municipal waste disposal facilities. A State with limited special waste facilities, on the other hand, tends to allow co-disposal of more wastes. If pretreatment is needed, it can be handled by the waste producer or by a private waste disposal company.

2.2 NETHERLANDS

In the Netherlands, the disposal of chemical wastes is regulated by the Chemical Waste Act, passed by Parliament in 1976. Implementation began in 1979. The Act prohibits depositing chemical wastes in or on the ground, except in urgent situations and under special conditions. Thus, chemical, physical, and biological treatments are the preferred methods for handling chemical wastes.

The following are alternatives for preventing the use of landfills:

- Limiting generation of wastes;
- Sorting at the source and reuse;
- Using as secondary materials and fuels;
- Treating and recycling (especially good for inorganic residues).

Chemical, physical, and biological treatment facilities, including incinerators, must conform to all applicable legal and regulatory requirements -- for example, the Public Nuisance Act, the Air Pollution Act, and the Water Pollution Act. Additionally, licenses are needed under the Chemical Waste Act. All chemical wastes require extensive control from generation to final disposal.

2.3 UNITED KINGDOM

Two major national laws govern the disposal of waste in the United Kingdom. The Deposit of Poisonous Waste Act of 1972 and the Control of Pollution Act of 1974.

The Deposit of Poisonous Waste Act was passed in response to the increasing number of cases of improper ash disposal. The Act penalizes the depositing of poisonous, noxious, and polluting waste on land if it might damage persons, animals, or pollute water supplies. The penalty for such an offense on conviction is up to 5 years imprisonment or an unlimited fine, or both. The Act also requires persons producing and/or transporting waste to inform waste disposal and water authorities about the nature and quantities of certain wastes being created or deposited in their jurisdictions.

Regulations issued under the Control of Pollution Act of 1974 require, among other things, the licensing of waste treatment facilities and landfill sites. In particular, effective control is exercised over site management, health and safety requirements, and water pollution aspects of landfills.

Section 17 of the Act had been intended to provide tighter control of the disposal of the more dangerous wastes. However, now that sites are licensed and guidelines issued for the disposal of such wastes in the Department's Waste Management Paper series, the emphasis of Section 17 is on maintaining records on the more dangerous wastes, which will be designated by an "inclusive list" system. When Parliament ratifies the regulations proposed under Section 17, the Deposit of Poisonous Waste Act will be repealed.

The following basic policies underlie the United Kingdom's view of hazardous waste management:

- The production of waste should be minimized as much as is economically and technically feasible,
- Wastes should be reused or recycled if economically and technically feasible,
- Wastes unavoidably created will be managed at licensed treatment or landfill disposal facilities,
- Although one disposal route theoretical may be better environmentally than another, the ready availability of licensed alternatives means that economic considerations will be of primary importance. Transportation will be a significant cost component. For example, a more expensive local option may be preferred instead of a cheaper, more distant one, because of transport costs.
- Pretreatment is not a prerequisite for disposal, but it facilitates disposal.

2.4 UNITED STATES OF AMERICA

The United States has had a policy dealing with various aspects of hazardous waste management for several years. The major legislative elements of the current hazardous waste policy are:

- The Federal Insecticide, Fungicide, and Rodenticide Act of 1972. This Act authorizes the Environmental Protection Agency (EPA) to regulate disposal and storage of waste pesticides and containers, including labeling requirements.
- The Safe Drinking Water Act of 1974. This Act authorizes EPA to set maximum contaminant levels for public drinking water systems and to control underground injection of waste. The States are to play the lead role in enforcing these regulations.
- The Toxic Substances Control Act of 1976 (TSCA). This Act authorizes EPA to obtain data on health effects of chemical substances and to regulate the manufacture, use, and disposal of a chemical substance or mixture where warranted.
- The Resource Conservation and Recovery Act of 1976 (RCRA). This Act is designed to regulate the management and disposal of solid and hazardous wastes and to promote the development of plans and facilities for the recovery of energy and other resources from discarded materials.

Hazardous waste management policy for the United States is contained in RCRA Subtitle C of the Act. It requires creation of programs for managing hazardous wastes to prevent serious risk of injury to health or the environment. The key provisions are:

- Identification of hazardous wastes.
- A system to follow wastes from point of generation to final disposal.
- A permit system, based on standards, for hazardous waste treatment, storage, and disposal facilities.

Under this program, the generator is be responsible for determining whether a waste is hazardous according to the identification criteria. If it is, the generator must either obtain a permit to manage the waste on-site or transport the waste to a permitted treatment, storage, or disposal facility. In the latter case, a manifest containing basic information about the waste must accompany each shipment to the point of final disposal. In either case, all treatment, storage, and disposal operations must meet the minimum standards.

The intent of RCRA is that hazardous waste management will be handled by the individual States. Each is to institute a program with requirements as least as stringent as those specified in regulations issued by EPA under RCRA. EPA will manage the program in any state that chooses not to accept the responsibility or does not meet the minimum EPA guidelines.

Before the RCRA program went into effect in 1980, most wastes were disposed of in landfills or open dumps. Subtitle C establishes special requirements for "secure" landfills to be used for hazardous waste disposal. Secure landfills will be significantly more costly than the former disposal methods. Also, recent publicity concerning hazardous waste landfills (for example, at Love Canal and the Valley of the Drums) has increased public awareness of the dangers of land disposal. The combination of higher costs and public opposition is expected to make reducing the generation of wastes and the recycling of waste components more attractive.

EPA is attempting to encourage the use of incineration and other treatment processes through regulatory policy and research, development, and demonstration projects. The purpose of these projects is to make technologies available to detoxify or destroy wastes, to reduce waste volumes, or to make waste materials more suitable for material or energy recovery.

2.5 OTHER NATO COUNTRIES

Some of the other NATO countries have in place, or are developing, national policies for the management of hazardous industrial wastes. The national policies presented here are considered to be representative.

3.0 TREATMENT PROCESSES FOR HAZARDOUS WASTE AND CURRENT APPLICATIONS

Hazardous waste treatment processes fall into four major categories: chemical, physical, biological and thermal. The following discussion addresses current applications of chemical, physical, and biological treatment methods. Methods employed in thermal treatment of hazardous waste (that is, incineration), are covered in the pilot study project report prepared by the Federal Republic of Germany.

Currently, the treatment of hazardous wastes is directed toward two goals:

- Minimizing the volume of hazardous waste requiring disposal or reclamation.
- Transforming the waste into a useable product or less hazardous form for reuse or disposal.

Available chemical, physical, biological, and thermal treatment methods provide the component parts for development of an overall management system. In developing an efficient and cost-effective system, a combination of techniques is tailored to the specific characteristics of the waste stream.

Information concerning 44 treatment methods for hazardous waste is summarized in Appendix I. The summary presents a synopsis of each process, data concerning current applications, estimates of capital and operating costs, and prospects for future applications.

3.1 PROCESS/WASTE MATRIX

A process/waste matrix (Table I) was developed to display all current applications of treatment processes to specific hazardous waste streams and compare their relative costs. Information was compiled from the following sources:

- Contributions from member countries.
- Open technical literature.
- EPA publications.

TABLE 1 - APPLICATION MATRIX OF CHEMICAL, PHYSICAL, AND BIOLOGICAL TREATMENT PROCESS TO WASTES

Process	Relative Cost Factor	Waste															Chem. Groups																		Specific Chems					
		Petrol Refin.	Petrochemicals	Pharmaceutical	Munitions	Paint&Ink Ind.	Painting Waste	PVC Production	Leather Tan.	Food Process.	Metal Fin. Liq.	M.F. Sludges	Pickle Liquor	Metallurg. Slag	Waste Oil	Chlor-Alkali	Carbonyls	Fluoride	Organic Acids	Inorganic Acid	Mercury	Cadmium	PNA's	Amines	Aromatics	Aliphatics	Ethers	Phthalates	Phenolics	Chlor. HC's	Cyanide	Sulfides	Pesticides	PCB's	PCP	2378-Dioxin				
arbon adsorption	Low	1	3	1	1	3	3	3			1					1					2	3	2	2	2	2	2	2	1	1		3	1	1	2	2				
il sep. techniques	Low	1	2					2							1																									
et air oxidation	High		3	2	3			3		3														3	3				3	3			3							
eutralization	Low				1						1	1			1			2	1												1									
hem. fixation/ecapsulation	Med.	3					2				1	1		2						2		2							3	3		2								
iltration	Low	1		1		3	2			1		1			1	1																	2							
x-reduction	Med.			3							1					1			2										1	2	1	1	3							
hem-precip/settling	Low	1		1		1	2		2		1	2	1		1	1						1			1		1	1			1	1								
vaporation	Low	2	3		1			3			1	1	2									3	2	2	1	2														
cid treatment	Low											3		1	1																									
istillation	Med.	1	2	1		2		2							2				2		2		1	1	1	1	1		1	1		2								
iotreatment	Low	1		1		1			1	1						3			1					1	1		1	1	1			1	2							
alcination	High	2					1				3	3																			3									
lotation	Low					1					3						3	2																						
ydrolysis	Low																																							
iq-liq. extraction	Low to High	1												2	3				2				3		3	3	2	3	2	1				3	2	2				
zonation	Med.			2							2						3						3						2	3	2	2	3							
hem dechlorination	High																													3			3	3		3				
V dechlorination	High																													3			2			2				
atalysis	High																2												3	3	3		3							
lectrodialysis	Low									2	3																													
everse Osmosis	Med.					3					2											2			3	2	3	2	3			2	2							
issolution	Low to Med.									2		3																												
on exchange	Med.	2			2						1		2			1				2		2							3	3	2	3	3	2						
icrowave	High					3																								3			3							
hlorinalysis	High																													2			2							
lectrolysis	High									3	3	3			2							3																		
ltrafiltration	Med.					2	2								2																									
iquid ion exchange	Low to High									3	3	3	3									3									3									
esin adsorption	Low																						2	2	2	2	2	2	3	3										

se Codes

1. Full Scale Common Use
2. Moderate Application
3. Research Stage

- Personal consultation with industry professionals.

Treatment processes were identified and placed in one of three categories:

- Category 1, full-scale common use.
- Category 2, moderate use.
- Category 3, research stages.

Categories 1 and 2 include all processes known to be in use in the United States or identified in literature from other member countries. Category 3 includes only technologies for which research projects could be readily identified. Thus, it may not include every waste treatment process currently being studied for possible application to hazardous wastes. The suitability of 30 processes was evaluated for 35 common hazardous wastes.

As the matrix shows, such recovery technologies are not generally in widespread full-scale use at present. Chemical, physical, and biological treatment can achieve two goals in hazardous waste management:

- To destroy hazardous constituents through techniques such as activated sludge treatment, calcination, and hydrolosis.
- To reclaim wastes through techniques such as distillation to recover organic solvents and electrolysis to recover metals.

4.0 POTENTIAL RECOVERY OF HAZARDOUS WASTES

Considerably more recycling is possible than is now being done. In the past, it has been less expensive to dispose of wastes in the cheapest way possible and to utilize virgin raw materials. The implementation of national policies on waste disposal is expected to change the economics of these practices. In some countries, however, more efforts are being made toward low-waste technologies rather than recycling.

4.1 FEDERAL REPUBLIC OF GERMANY

Waste oils and waste solvents are the only dangerous wastes presently extensively recycled in the Federal Republic of Germany. The relatively high cost of processing most wastes, as compared with current raw material costs, discourages recycling. Also, wastes are not collected separately at the point of origin and may be mixed during transportation, making it technically impossible to separate out the constituents.

Many chemicals recovered from wastes can be used in primary production only after purification. However, they may be usable in other applications that do not demand the high degree of purity of the initial materials. For example waste acids and alkalis are used in disposal plants to neutralize other waste materials. Waste solvents can be distilled to separate them from their contaminants. Electroplating concentrates and sludges are also suitable for recovery of nonferrous metals. These processes are in use or can be developed from known processes.

About 100 recycling plants are in operation in the Federal Republic. The cost of extracting, processing and transporting the virgin raw materials puts a ceiling on recycling costs. Future developments are, therefore, increasingly aimed at developing technologies that produce no waste in the first place.

4.2 NETHERLANDS

Because hazardous wastes cannot be deposited in or on the ground in the Netherlands, industry is working to limit the generation of wastes by process changes. Recycling is now limited to a narrow range of wastes, including:

- Catalysts (for precious metals, cobalt, nickel, and copper).
- Sludges (for copper).
- Pickling baths.
- Photographic waste (for silver).
- Acids.

Certain types of wastes containing heavy metals are potentially recoverable if concentrations are high compared to raw ores or their concentrates. In most cases, wastes contain a greater number of metals than the ores. Thus the recovery processes need to be able to separate iron, copper, chromium, zinc, nickel, lead, and cadmium.

Pending results of R&D, temporary storage for 5 to 10 years is a part of the overall management philosophy. The storage technique and the selection of wastes are being evaluated.

4.3 UNITED KINGDOM

In the United Kingdom, the Chemical Recovery Association is the non-profit organization carrying out the aims and activities of commercial companies, individuals, and public agencies concerned with resource recovery of chemical by-products.

A central ion-exchange regeneration plant has been set up, and companies are being set up in the Midlands to precipitate and filter metal-finishing waste liquors for the reclamation of heavy metals.

4.4 UNITED STATES

When RCRA was passed in 1976, it was the first comprehensive Federal legislation to deal with the hazardous waste issue. Under RCRA, EPA has developed a phased strategy to waste management:

- To reduce the generation of wastes at the source by improving production processes, improving durability and product life, and other techniques.
- To remove both materials and energy from wastes to maximize recycling and resource recovery.
- To ensure that those wastes that cannot be eliminated or recovered are stored, transported, treated, and disposed of by procedures that protect public health and the environment.

Hazardous waste regulations issued under the final element of the strategy, have made it more economically attractive for companies to seek potential uses for valuable components of their wastes. Some uses may be identified through waste exchanges.

Since 1975, a number of waste exchanges have been set up by trade associations, chambers of commerce, universities and, in some cases, state and local governments. Even though only a small percentage of wastes is suitable for exchange, the waste exchanges make a valuable contribution by reducing the amounts of materials to be managed by less desirable options.

Other positive signs are encouraging resource recovery from wastes. For example, the Interstate Commerce Commission is under court order to review freight rates for virgin materials because recyclers claim the rates discriminate against their products. In addition, the Energy Tax Act of 1978 provides industry with a 10 percent tax credit for the purchase of recycling equipment.

4.5 OTHER NATO COUNTRIES

Othe NATO countries are making progress in the recovery of hazardous wastes. The examples presented in this section, submitted by the project committee members, are considered representative.

5.0 WASTE TREATMENT CENTERS IN NATO COUNTRIES

The concept of centralized waste treatment facilities is relatively new, and is being pursued in many of the NATO countries.

5.1 DENMARK

The treatment of hazardous waste in Denmark is concentrated around Kommunekemi, a corporation founded in 1971 by the Danish municipalities. The objective is to eliminate oil and chemical wastes from the whole of Denmark and to recycle any valuable substances in the wastes for use in industry or in energy products. The municipalities acted because their refuse dumps and sewage systems were receiving commercial and industrial wastes, which had led to an unacceptable level of pollution.

Establishing Kommunekemi was a complicated undertaking, requiring the following actions:

- A law had to be passed covering disposal of waste dangerous to the environment.
- Estimates had to be made of the quantities and types of waste involved.
- An organization had to be developed to collect and transport wastes.
- The necessary treatment plants had to be planned and built. Capacity must cover development over a 5-year period.
- An economic basis had to be established, both for the building of the plants and for their day-to-day operation.

A regulation covering disposal of oil waste took effect in October 1972, the chemical waste regulations, April 1976. These regulations stipulate that all waste must be reported to the authorities, and that an industry must deliver all hazardous wastes to the central facility, unless the industry can show that it can dispose of the waste in a reasonable fashion.

The municipalities are obligated to receive the waste. Therefore, 20 central collection stations were established, at least one in each of Denmark's 14 counties. In addition, each municipality has to establish at least one collection point in its area, where private citizens, at no cost, can deliver their refuse. From the collection stations, the waste is sent by rail to the Kommunekemi plant.

Construction of the plant begun at Nyborg in 1972 and was completed in November 1975. The location is central, both in regard to transportation and industrial activity. The plant includes the following:

- The receiving plant, storage tanks, and warehouses.
- Laboratory.
- Plant for treatment of oil waste.
- Plant for treatment of inorganic chemical waste.

- Incinerator for solid and liquid organic waste with energy recovery.
- Incinerator for pumpable organic wastes containing halogens.
- Depositing site (controlled landfill).

Between 1976 and 1978, the following were added:

- A surface and an underground tank basin for Danger Class 1 products with a total capacity of about 2,500 cubic meters.
- A second warehouse for storage of solid organic waste in containers.

A third phase due to be completed by 1982 included the following:

- A new incinerator for solid and liquid organic waste with a capacity of 30,000 tons per year.
- An oil treatment plant with a capacity of 25,000 tons per year.

5.2 FEDERAL REPUBLIC OF GERMANY

5.2.1 Bavaria

In the State of Bavaria, two integrated incineration, treatment, and disposal centers have been established as government-industry joint ventures for commercial and industrial "special wastes", which cannot be disposed of with municipal wastes in existing facilities. One center has been operated by the Zweokverband Sondermullplatze Mittelfranken in Schwabach since 1968, the second, by the Gesellshaft for Sondemullbeseitigung in Bayern (GSB), near Munich, since 1971. The GSB also operated transfer stations since 1971. Special waste is subdivided into:

- Substances which, because of possible air and water contamination, can only be deposited at special sites under special conditions — for example, oil contaminated soil, tar residues, hardening salt, and acid sludges.
- Substance which can or must be disposed of by burning, for example, solvents and oily residues.

- Substances which require chemical or physical treatment prior to disposal, for example, acids, alkalies, sludges from the chemical and metal processing industries, and water-soluble heavy metal salts.

Prior to treatment, these substances are analyzed to determine the processes to be used and to ensure that the wastes have been correctly identified by the delivering party. The treatment itself generally consists of one or more of the following processes:

- Neutralization and decontamination.
- Dewatering by chemical, mechanical, or thermal processes.
- Clarification of wastewater to prepare it for discharge into a sewer system or a receiving stream.
- Incineration.
- Disposal in municipal sanitary landfills or secure landfills.

The centers pretreat, incinerate, and also operate landfills. They are equipped with dewatering, neutralization, detoxification, and wastewater treatment facilities such as sludge thickeners, filter presses, emulsion separating equipment, and mixing equipment. A wastewater collected in tanks is pretreated prior to discharge into the municipal sewage system where it is treated with municipal sewage.

5.2.1.1. Collection Points

At present, there are seven special waste collection points in Bavaria. Small amounts of various wastes are collected from local industrial plants. All collection points have, in addition to an operations building with testing lab and a vehicle scale, large storage areas. Besides providing temporary storage, the collection points also pretreat as much of the wastes as possible and reduce their volume. They have wastewater purification facilities to separate oil and water mixtures into oil, water, and solid components. The purified wastewater is discharged, leaving less than 10 percent of the original material for transport.

Some facilities are also equipped for neutralization and, if necessary, sludge thickening.

5.2.1.2. Recycling Plants

In 1973, GSB acquired a plant for distilling used solvents, paint thinners, degreasing agents, and the like and selling the reclaimed products. An incinerator at one of the centers produces heat and electrical energy for its own center's needs.

5.2.1.3. Transport

Industrial plants can transport special wastes to the collection points or they can hire private firms that guarantee delivery. The waste is transported between collection points and disposal plants, again by private firms, in containers or tank vehicles.

5.2.1.4. Waste Quantities and Investments

GSB has more than tripled its deliveries of special wastes (thousand tons) since 1972:

1972	1973	1974	1975	1976	1977	1978	1979
60	116.5	134	165	171.5	184.5	183.1	190

GSB spent about 70 million German marks on their facilities as of the end of 1976. The State granted large subsidies and low-interest loans for this project.

5.2.2. Other States

Other States of the Federal Republic have no such integrated treatment and disposal centers. There are, however, almost 20 smaller treatment facilities distributed all over the country (see Table 2). The various centers offer such services as detoxification (cyanide oxidation, chromate reduction), neutralization, oil emulsion separation, and sludge dewatering. Some of these centers operate their own landfills for the residual sludges.

TABLE 2

List of Central Treatment Facilities in the Federal Republic of Germany

Place	State	Type of treatment
Albstadt	Baden-Wurttemberg	detoxification neutralization
Altena	Northrhine-Westphalia	neutralization
Arnsberg	Northrhine-Westphalia	detoxification netralization sludge dewatering
Bielefeld	Northrhine-Westphalia	detoxificaiton neutralization sludge dewatering
Bramsche	Lower Saxony	detoxification neutralization
Bremen		detoxification neutralization
Ebenhausen	Bavaria	detoxification neutralization emulsion separation sludge dewatering
Hamburg		detoxification neutralization sludge dewatering
Heiligenhaus	Northrine-Westphalia	sludge dewatering
Idar-Oberstein	Rhineland-Palatinate	detoxification neutralization sludge dewatering

TABLE 2 (cont'd)

Place	State	Type of treatment
Iserlohn	Northrhine-Westphalia	detoxificaiton neutralization emulsion separation sludge dewatering
Koln-Niehl	Northrhine-Westphalia	detoxification neutralization emulsion separaton
Lippstadt	Northrhine-Westphalia	detoxification neutralization emulsion separation sludge dewatering
Ludenscheid	Northrhine-Westphalia	sludge dewatering
Munchen	Bavaria	detoxification neutralization
Osnabruck	Lower Saxony	neutralization
Salach	Baden-Wurttemberg	emulsion separation sludge dewatering
Schwabach	Bavaria	detoxification neutralization emulsion separation sludge dewatering
Tuttlingen	Baden-Wurttemberg	detoxification neutralization sludge dewatering
Wutoschingen	Baden-Wurttemberg	emulsion separation sludge dewatering

5.3 FRANCE

France currently has four broad-sprectrum waste management centers.

5.3.1. Saint Vuilbas Center

Saint Vuilbas Center has been operated by Plafora, S.A. since 1975. It contains four prinicipal units:

- An incineration unit consisting of:
  - a drum-type furnace for incinerating solids;
  - a post-combustion chamber;
  - a radial current scrubber for purifying combustion gases.
- A physical-chemical detoxification unit involving several processes
  - neutralization;
  - chromium removal;
  - removal by catalytic or electroytic oxidation;
  - treatment of soluble oils.
- An ion-exchange resin regeneration unit.
- A sludge dehydration unit.

The wastes treated are:

- Incinerable solid wastes (soiled packing, chlorinated plastics, etc.,).
- Mineral sludges containing heavy metal salts.
- Acid and alkaline solutions.
- Cyanide and chromium solutions.
- Quenching salts.
- Soluble oils (emulsified cutting fluids).
- Paint wastes, degraded chemical products, etc.

Capacities at the center are:

- Incineration: 20,000 metric tons/year
- Physical-chemical: 18,000 metric tons/year
- Sludge dehydration: 5,000 metric tons/year

5.3.2. Mitry Compans Center

The Mitry Compans Center has been operated by GEREP-CA since 1977. It contains two principal units:

- An incineration unit consisting of:
  - a fixed furnace (5,000 th/h) for pumpable, non-corrosive liquid wastes;
  - a rotary furnace (2,500 th/h) for plastic and corrosive wastes (chlorinated and sulfurated);
  - a wet dust removal tower shared by the two combustion chambers;
  - a recovery steam generator.
- A physical-chemical detoxification unit which fixes and stabilizes sludge by polymerization (SOLIROC).

The wastes treated are:

- Incinerable liquid wastes, particularly chlorinated and sulfurated wastes.
- Incinerable powered plastic and solid wastes.
- Chromium solutions.
- Acid and basic solutions containing no cyanide or hexavalent chromium.
- Alkaline sludges containing no cyanides.
- Chlorinated wastes by chemical treatment: (amount limited to 10 percent maximum chlorine content in the waste by weight).

Capacities at the center are:

- Incineration: 18,000 metric tons/year
- Detoxification: 5,000 metric tons/year

5.3.3. Limay Center

The Limay Center has been operated by SARP Industries since 1975. It contains four principal units:

- An incineration unit which includes a liquid injection 5,000 th/h furnace.
- A physical-chemical treatment unit involving several processes:
  - sludge neutralization and precipitation;

  - chromium removal (using ferrous sulfate);
  - cyanide removal by catalytic oxidation;
  - treatment of laboratory waste.
- A sludge stabilization unit using the CHEMFIX procedure.
- A unit for recovering copper in ammonia solutions from the electronics industry (printed circuits).

The wastes treated are:

- Incinerable non-corrosive liquid wastes (hydrocarbons, phenol-water, organic sludges, solvents).
- Alkaline acid baths.
- Wastes from surface treatment industries.
- Wastes containing heavy metal salts.
- Cyanide solutions.
- Quenching salts.
- Laboratory wastes.
- Ammoniacal copper solutions.

The capacities at the center are:

- Incineration: 15,000 metric tons/year
- Physical-chemial detoxification: 35,000 metric tons/year
- Regeneration of ion-exchange resins: 100 cubic meters/year
- Laboratory wastes: 400 metric tons/year
- Copper recovery: 3,000 metric tons/year
- Sludge stabilization: 100,000 cubic meters/year

5.3.4. Hombourg Center

The Hombourg Center has been operated by P.E.C. Engineering since 1974. It contains four principal units:

- A chemical treatment unit, involving several processes:
  - sludge neutralization and precipitation;

  - chromium removal (reduction by sulfur dioxide);
  - cyanide removal by catalytic oxidation.
- A sludge stabilization unit using the PETRIFIX procedure.
- A regeneration unit for ion-exchange resin cartridges.

The wastes treated are:

- Incinerable liquid wastes (hydrocarbons, solvents, organic sludges).
- Acid or alkaline baths.
- Wastes from surface treatment industries.
- Sludges containing heavy metal salts.
- Quenching salts.
- Soluble oils.

The capacities at the center are:

- Incineration: 3,000 metric tons/year.
- Physical-chemical detoxification:
  - neutralization: 25,000 metric tons/year;
  - chromium removal: 2,000 metric tons/year;
  - cyanide removal: 800 metric tons/year.
- Sludge stabilization: 30,000 t/year.
- Ion-exchange resin regeneration: 1,000 cartridges/year.

5.4 UNITED KINGDOM

There are several privately owned waste treatment centers operating in the United Kingdom. Usually they involve the chemical processing of inorganic material and incineration of organics. Inorganic materials handled by these facilities include: sulphuric, nitric, hydrochloric, phosphoric, and hydrofluric acids; and metal and cyanide wastes from metal processing operations, which include chromium, copper, cadmium, nickel, tin, zinc, iron, and cobalt. For example, cyanides are converted to relatively non-toxic cyanate by treatment with chlorine in alkaline solution; heavy metals are converted to insoluble hydroxides by treatment with alkali; and chromates are reduced to trivalent chromium.

If a product can be used, it is. Nonsaleable products are dewatered and sent to a licensed landfill. The wastewaters from the processes are treated before discharge to a sewer under conditions issued by the water authority. In some cases, an incinerator can destroy wastes or more than one physical type such as: liquids and sludges, thermoplastic solids, conventional solid waste contaminated with toxic chemicals, and drummed material.

There are also several small waste treatment companies in the United Kingdom. Typically, neutralization of acids, reduction of hexavalent chromium, and precipitation of metal hydroxide are carried out. Several companies recover waste oils. A cental ion-exchange regeneration facility is operating in a region where metal finishing wastes are produced. One company mixes latex wastes, heavy oils, and paint wastes with coal fines to make a fuel for firing a local power station. A copper refiner takes in copper-bearing wastes. Several companies take in ammonium and phosphate wastes in order to product nitrogen/phosphorous/potassium fertilizers. There are, of course, many in-house waste treatment plants utilizing various processes, but relevant information has been difficult to obtain.

Without doubt, a great amount of waste is being treated in the United Kingdom. The Department of the Environment, through its Waste Management Paper Series, is endeavoring to further this by encouraging centralized facilities, particularly in the case of metal-finishing and solvent wastes.

5.5 UNITED STATES

There are a number of treatment and disposal facilities operating in the United States which accept a variety of hazardous waste materials. The majority of facilities are owned and operated by private industry. The facilities are classified as either off-site or on-site, depending on where the waste is generated. The Federal regulations issued under RCRA will have significant impact on the activities of the treatment and disposal facilities. Some facilities may have to improve their operations to meet the regulations. A number of companies are interested in the hazardous waste management industry, but will not begin serious planning until the final regulations are issued.

The exact number of treatment and disposal facilities, both off-site and on-site, will not be available until late 1981. It is estimated that there are at least 313 off-site facilities in the United States. Disposal technologies include incineration (rotary kiln, liquid injection, fluidized bed, and other methods) and land disposal (secure landfill, sanitary landfill, soil incorporation/landfarming, encapsulation, lagooning, and other methods). Of the 313 facilities, at least 44 practice some form of incineration, and 117 practice some form of land disposal. At least 123 facilities are involved in collection/hauling, 89 in processing/ treatment, and 116 in recycling/reclamation.

At this time, there is no good estimate of the number of on-site treatment facilities. Facilities located on-site generally employ the same methods of treatment and disposal as those facilities located off-site. However, in many industries the method of treatment or disposal is specific for a given waste or is the only method available.

Typical of the central off-site facilities expected to be developed in the future is one being designed by a major waste management corporation for a highly industrialized region in Southern Louisiana. This facility is to be operated by a private corporation, but the funding is to be through the sale of State-guaranteed tax exampt bonds. Industry benefits by a cost-effective means of meeting the Federal regulations. The State benefits by the elimination of environmental and health hazards and also by continued industrial growth.

The processes planned for this facility include: acid distillation, toluene distillation, solvent extraction, rotary kiln incineration with heat recovery, chemical precipitation and neutralization, carbon absorption, chemical fixation, activated sludge, screening, clarification, dewatering, treated effluent discharge, and a secure landfill.

In conclusion, the majority of the treatment and disposal facilities in the United States are privately owned. They employ a wide variety of techniques for the treatment and/or disposal of hazardous waste materials. Off-site facilities usually serve a whole industrial region. In the future, partial or total State-funding of such facilities may become more common.

5.6 OTHER NATO COUNTRIES

Centralized waste treatment facilities are also in place or are being developed in other NATO countries. The examples presented here, submitted by the project committee members, are considered representative.

6.0 RESEARCH AND DEVELOPMENT EFFORTS

Considerable research and development is underway on chemical, physical, and biological treatment of hazardous industrial wastes. Much of the work shows potential for increased application. Expanding regulatory activities are expected to spur research and development efforts, and changing economics are expected to encourage use of the processes developed.

6.1 NETHERLANDS

6.1.1. Immobilization Techniques for Metal Sludges

The last few years have seen the patenting of many techniques aimed at reducing the environmental burden due to heavy metal leachate from waste materials (for example, metal hydroxide sludges). These techniques reduce the leaching of heavy metals by transforming the waste into a product in which the metal compounds are physically and/or chemically immobilized.

Four of these immobilization techniques have been tested on a synthetic metal hydroxide sludge containing mercury, arsenic, cadmium, copper, and iron. Leaching tests were elected that measure only the chemical aspects of the leachability of the sludge. Physical aspects such as reduced permeability were not included.

Two types of leaching tests were used — stirring and soxhlet extractions. The stirring tests showed little or no reduction in leaching due to chemical immobilization. In fact leaching increased when the pH was decreased. The soxhlet extractions showed a decrease in leaching of cadmium from all four immobilized products (probably due to pH), of copper from three products, and of mercury for one product. Only one immobilized product showed no change in leaching of arsenic as compared with the synthetic sludge; the other three showed an increased leaching.

The X-ray element distributions of the immobilized products were obtained by scanning electron microscopy. The results did not clearly show any interaction between the elements of the synthetic sludge and the elements of the immobilizing agents; this observation was restricted to microscopically detectable separate phases.

This investigation indicated that the four immobilization techniques studied rarely reduce the chemical leachability of the synthetic sludge.

6.1.2 Recycling of Complex Heavy-Metal Wastes

Solvent extraction and ion exchange are useful for selective removal of metals from aqueous waste streams. Their application to wastes is relatively new.

An investigation was conducted to develop a process based on solvent extraction, to recover pure sulfates of copper, nickel, and zinc from metal hydroxide sludges. The process is based on a selective leaching step of the metals under such conditions that all three, and chromium as well, partly dissolve. Iron remains in the residue.

One objective was to develop an appropriate extractant to separate these metals. As an alternative to the commonly used "LIX-agents", a new agent was developed: a mixture of cyclohexanone oxime and oleic acid. This agent separates the metals on the basis of pH. Laboratory investigation showed the feasibility of the process and the high quality of the copper and zinc salts. An important advantage of this proces is that only one extractant is needed, and it is fairly inexpensive.

The aim of another investigation was to develop a process to recover all heavy metals from several metal wastes, and to leave a nonhazardous residue. In the process, all metals are dissolved from the waste in hydrochloric acid. The solution is passed through an ion exchange column where copper, lead, zinc, and cadmium are fixed as chloride complexes, while chromium, nickel, manganese, calcium, and sodium pass through. Nickel and chromium can be separated from this solution via several techniques, for example, elecrolysis. Manganese can then be precipitated out. The copper, lead, zinc, and cadmium are dissolved out with hydrochloric acid of decreasing strength. The acid is recovered from the lead and copper solutions by distillation in the presence of sulfuric acid. The zinc and cadmium solution can be treated by a cation exchanger to obtain sulfates. If necessary, electrolysis can be applied to obtain the metal as elements with a purity of greater than 99.9 percent. Investigations are in progress on fly ash from municipal and industrial incinerators.

6.2 UNITED STATES

Research in the following areas is being conducted by EPA's Municipal Environmental Research Laboratory.

6.2.1 Leachate Treatment

An evaluation of leachate treatment was conducted in two phases. In Phase 1, leachate generated from landfills located in different parts of the United States were analyzed with emphasis on the chemical analysis of organic constituents and heavy metals. Phase 2 involved the biological and physical-chemical treatment of organic matter from solid waste leachate.

6.2.2 Sanitary Landfill Stabilization

In this study, different leachate treatment schemes were applied to simulated landfill leachate. Treatments were compared with the leachate being recirculated through the landfill, with leachate being recirculated with pH control and initial sludge seeding, and with leachate being treated by aerobic and anaerobic processes.

6.2.3. Preprocessing Technologies

A study is being conducted to identify, screen, and develop preprocessing technologies that convert hazardous wastes into the best condition for cost-effective treatment or disposal.

6.2.4. Data Bank

A program is under way to develop a data bank on all existing, emerging, or future hazardous waste control technologies to:

- Develop a data bank on past, present, and future pesticides, organic, and inorganic chemical disposal problems, including data on quality, composition, location, generation, toxicity and storage.
- Develop a matrix relating treatment techniques to disposal problems/pollutants.

6.2.5. Control of Inorganic Wastes Discharged to Municipal Facilities

This project seeks to develop techniques -- electrolysis, high gradient magnetic separation, distillation, and filtration, for example -- to recover isolate, or neutralize inorganic hazardous wastes, including heavy metals, that are (or may be) discharged to the municipal landfills, surface impoundments, and hazardous waste management facilities.

In Phase 1 of this project the literature will be reviewed and data acquired on potentially applicable processes and processes currently in use. Leachate generation relating to heavy metals will also be reviewed. Phase 2 consists of a more intensive analysis and evaluation of promising treatment systems. The four most promising techniques will be selected for testing on landfill leachates and other hazardous wastes. Phase 3 consists of the demonstration/verification of the selected techniques at one of more polluted municipal landfill, surface impoundment, or public water source. Also, the techniques will be evaluated for use on sludges and contaminated sediments, as preparation for encapsulation.

6.2.6. Treatment of Aqueous Wastes from Army Pest Control Facilities

This study is evaluating a filtration/absorption system for treatment of wastes generated by Army pest control facilities. The system was designed for batch operation using an activated carbon element and, if necessary, additional elements employing other adsorbents. The capacity will be up to 1,000 gallons of wastewater per batch treatment, and the effluent water should be suitable for reuse in the facility or for discharge into a sanitary sewer.

6.2.7. Reaction of Molten Sodium and Solvent with PCB

This study was conducted to determine the applicability of the sodium polyethylene glycol process to dechlorination of organic compounds. Work at the small bench-scale level has demonstrated that:

- PCB's and other halogenated compounds can be converted to potentially useful substances (polymer precursors and plasticizers).
- Costs do not appear prohibitive.
- Partial dehalogenation is an effective detoxification mechanism.

6.2.8. Biological Treatment

Biological treatments are being investigated to determine if they can effectively destroy pesticides and other hazardous chemicals. Biological treatment of municipal and industrial waste is common. However, little is known about its applicability to destruction of pesticides. Some widely used methods available for biological treatment of pesticides are:

- Activated sludge.
- Trickling filter.
- Oxidation lagoon.
- Anaerobic digestion.
- Soil incorporation.

6.2.9. Pit Disposal of Pesticides

To evaluate the effectiveness of pit disposal of pesticide materials, the following steps were initiated:

- Evaluate the overall effectiveness of the pesticide disposal pits currently in use on materials previously deposited.
- Determine the presence or absence of environmentally hazardous compounds.
- Continue to sample each pit throughout the study.
- Establish experimental systems for studying the fate of selected pesticides in isolated micropits under controlled conditions.
- Evaluate biological activity in present systems.
- Develop plans and specifications for construction and management of disposal systems and for regional implementation.

After approximately one year, chemical and microbiological data indicated no build up of pesticide residues. The number of microbes was similar to what would be expected in a pit of this type even if no pesticides were present. The flora, however, were less diverse than would be expected in an open pit.

6.2.10. Sodium Treatment of PCB

A new treatment process involves cleaving the carbon-chloride bonds of PCB with sodium. Laboratory experiments demonstrate that both sodium metal and sodium napthalide are effective. However, sodium napthalide is preferred because the reactions were extremely rapid and can be performed at room temperatures in either glass or steel vessels. This process can reduce the concentration of PCB in wastes from 130 ppm to less than 10 ppm.

The process has been adapted for use on a commercial scale and has proved to be: selective, usable on-site in existing equipment, adaptable to small or large scale operation and relatively low in cost. In addition, it can be used to treat other materials such as polybrominated biphenols (PBBs), halogenated pesticides, and tetrachlorobenzodioxins.

6.2.11. Ultraviolet Destruction of TCDD

This project is investigating the potential of photolysis for destroying 2, 3, 7, 8-tetrachlorodibenzodioxin (TCDD) at a facility that generated several thousand gallons of TCDD-contaminated waste over a period of years. This procedure destroys part of the dioxin by exposing it to ultraviolet light in the presence of a proton donor. Small batches can be destroyed at low temperatures and pressures.

6.3 UNITED KINGDOM

Of interest in the United Kingdom is an investigation into the microbiological sequestration of heavy metals, initially cadmium, through the development of highly selective strains of bacteria; also the biodegration of intractable organic wastes, such as PCBs, through the development of specialized bacteria.

6.4 OTHER NATO COUNTRIES

Some other NATO countries are also involved in research and development on chemical, physical, and biological treatment. The studies presented here are the most comprehensive contributions and should be considered representative.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

(a) Most chemical, physical, and biological treatment processes can reduce the volume or hazard of waste. However, a residue usually remains that may require further treatment or disposal. Hence, chemical, physical, and biological treatment by itself is not always a cure-all.

(b) Some conventional chemical, physical, and biological treatment processes (such as neutralization) are well developed and widely applied to hazardous wastes at both on-site and centralized off-site facilities. Other processes are specific to particular wastes and are usually applied by the waste generator at on-site facilities.

(c) Chemical, physical, and biological treatment processes have the best potential to recover resources from wastes. Such recovery can play an important role in reducing the quantities of waste going to land and ocean disposal.

(d) Technology for resource recovery and recycling of materials from hazardous waste is still in its early stages of development, except for waste oil and waste solvents.

(e) In most NATO countries, information on chemical, physical and biological treatment of wastes on-site is proprietary and therefore is difficult to obtain.

(f) In many NATO countries, chemical, physical, and biological treatment processes are widely used. Restrictions on land disposal, specific regulatory requirements for resource recovery, and financial incentives will further increase resource recovery by chemical, physical, and biological treatment.

(g) The recent increase in construction and operation of centralized treatment facilities in European NATO countries is expected to be repeated in Canada and the United States following implementaion of regulatory programs. Much activity is anticipated over the next 5 to 10 years.

(h) In many NATO countries, centralized chemical, physical, and biological facilities are for the most part privately owned. However, in a few cases, centralized facilities have been partially or wholely underwritten by regional or local authorities.

(i) Research and development of chemical, physical, and biological treatment is being actively pursued by national governments, industry, and other organizations in many NATO countries.

7.2 RECOMMENDATIONS

(a) In evaluation of hazardous waste management alternatives, resource recovery by chemical, physical, and biological processes should be encouraged before thermal treatment, or land or ocean disposal.

(b) Use of chemical, physical, and biological treatment processes for hazardous waste should be encouraged as a means to improve environmental protection.

(c) The research and development efforts of the member NATO countries, particularly in resource recovery from wastes and treatment of chlorinated organic wastes, should be encouraged where these processes are appropriate for environmental protection and are expected to be economically and technically viable.

(d) Increased efforts are needed among nations to exchange information on hazardous waste treatment methods. Development of a uniform hazardous waste nomenclature system would facilities this exchange of information.

(e) The role of chelmical, physical, and biological treatment, including both on-site and centralized facility application, should be further evaluated in the context of the overall hazardous waste management system. The Organization for Economic Cooperation and Development (OECD) would be an appropriate organization for such an evaluation.

(f) Many chemical, physical, and biological treatment processes, especially those with potential for resource recovery, can and should be applied to non-hazardous industrial wastes, where technically and economically feasible, to reduce the amounts of waste requiring land or ocean disposal.

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Appendix

This Appendix is a summary of a United States sponsored study of the state-of-the-art of treatment processes for hazardous waste managements. It represents a detailed summary of potential treatment methods along with guidance on selection of treatment for many waste types. Although the report was written in the context of United State's waste problems, the chemical processes are universal.

PHYSICAL, CHEMICAL, AND BIOLOGICAL TREATMENT TECHNIQUES FOR INDUSTRIAL WASTES

Executive Summary

This is the executive summary from the final report (SW-148c)
which describes work performed
for the Federal solid waste management program
under contract No. 68-01-3554
and is reproduced as received from the contractor

Volumes I and II examine 47 unit engineering processes for their applicability to the task of treating hazardous industrial wastes.

Copies of both volumes will be available from the
National Technical Information Service
U.S. Department of Commerce
Springfield, Virginia 22161

U.S. ENVIRONMENTAL PROTECTION AGENCY
1977

This report was prepared by Arthur D. Little, Inc., Cambridge, Massachusetts, under Contract No. 68-01-3554.

Publication does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of commercial products constitute endorsement by the U.S. Government.

An environmental protection publication (SW-148c) in the solid waste management series.

FOREWORD

There is a strong need for treatment processes which can detoxify, destroy, or apply resource recovery principles to industrial wastes. This study examined 47 unit engineering processes for their applicability to the task of treating hazardous industrial wastes.

Of these unit processes, 10 can be applied for phase separation, 3 are basically for pre-processing of bulk solids or tars, 12 react chemically to destroy or detoxify the hazardous components, while 25 can be used to separate specific components within the waste stream. Some of these unit processes are commonly used for industrial waste treatment while others require further R&D efforts before they will become commercially attractive. Four (dialysis, electrophoresis, freeze drying and zone refining) were found not to be applicable to waste treatment.

Part Two of this report presents comprehensive descriptions of each of the unit processes, including information on the basic principles, areas of application, economics, energy and environmental considerations, and an outlook for future use on industrial wastes. Thus, Part Two is in essence an up-to-date reference textbook on potential treatment processes.

A major problem is how to make all of the information in Part Two readily available and useful. Section IV of Part One focuses on that problem, and is organized as a series of reference tables to be used when screening processes for application to an individual waste stream. These tables will provide a method of screening out processes that do not have any potential for the waste in question.

PREFACE

BASES FOR COST ESTIMATES

All capital cost estimates were prepared on the basis of equipment and construction costs for a time period of early 1976. The bases used were either the Chemical Engineering Plant Cost Index of 188 or a Marshall and Swift Equipment Cost Index of 450, (Reference – Chemical Engineering March 29, 1976) for all of the processes except those based on biological activity. For the biological processes, the cost basis was the Engineering News Record Construction Cost Index (ENR March 18, 1976) of 2300.

Operating labor costs were taken as $12.00/hour which was assumed to include supervision and overhead charges. Annual maintenance (labor and material) was taken as a fraction of investment and was varied according to the estimated severity of the operations. Chemicals were charged at unit prices derived from Chemical Market Reporter. Electricity was charged at $0.02/kwh.

The annualized costs of capital were established on the basis of a 10-year capital recovery factor with money borrowed at 10 percent interest. This method of annualizing capital costs has been widely used in pollution control cost estimating and is equivalent to off-the-books financing that might be obtained through the use of industrial pollution control bonds. The capital recovery factor for these cost estimates is 0.16274, i.e., the annual cost of capital is 16.274 percent of the total capital investment.

If cost estimates are to be prepared for different capacities, the following exponential scaling factors based on capacities are suggested.

Capital Investment	
All processes except biological	0.7
Biological processes	0.5
Operating Labor	0.3
Utilities and chemicals	1.0

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PART ONE

SUMMARY

I. BACKGROUND

A typical manufacturing establishment takes in raw materials, adds value through one or more processing steps, and produces one or more products for sale. It is seldom possible to convert 100% of the raw materials into salable products, so there almost always is some waste or residual. In addition, there are usually gaseous and aqueous emissions, but recent air and water pollution control regulations limit the release of potentially hazardous materials in effluent water and gas streams. Water treatment and air pollution control systems usually act to remove rather than to detox fy hazardous materials. Potentially toxic or hazardous materials removed from air and water streams, or generated as waste in the course of normal industrial production, are not currently subject to Federal regulation; and most frequently these residual waste materials are dumped on land.

Indiscriminate dumping of industrial processing wastes can lead to groundwater contamination, or other adverse effects, often 40 or 50 years after the initial waste disposal. Although methods have been explored to reduce leaching to groundwater, by, for example, encapsulating wastes prior to burial, and/or securing sanitary landfills, the amount of land available for dump sites still is decreasing, while the volume of residuals requiring disposal is increasing.

As a normal course of events, large industrial plants are constantly seeking ways to convert process residuals into profitable by-products that can either be returned to the raw material stream within the plant, or marketed outside. The success of such resource recovery efforts is governed almost entirely by economics. The net costs of recovery (actual treatment costs minus credits for the recovered resource) must be less than the costs of alternative waste management methods. As long as the alternative of land dumping at $2-3/ton remains, the economically allowable investment in waste treatment is severely restrained. Clearly, however, continued release or re-release of contaminants into the environment via leaching to groundwater, surface water run-off, or airborne dusts from land burial sites cannot be permitted. As land disposal costs begin to increase in response to pressures for protecting the environment, other hazardous waste management alternatives can become more attractive.

For the management of industrial processing wastes from the point of generation to the point of ultimate (and environmentally adequate) disposal, three technically desirable alternatives to immediate land burial are:

- resource recovery (materials or energy),
- detoxification, and
- volume reduction, coupled with disposal.

The resource recovery alternative is obviously attractive not only from the point of view of conserving materials supplies now beginning to be recognized as finite, but also as a potential means of reducing the quantity of hazardous material requiring disposal. The detoxification alternative interposes a step prior to disposal that makes the waste stream innocuous, so that lowest-cost disposal methods become applicable. The volume-reduction alternative simply reduces the magnitude of the waste disposal problem, permitting efficient utilization of available secured chemical landfill sites.

II. SCOPE OF THE STUDY

A. OBJECTIVES

The objectives of this study are to identify physical, chemical, and biological treatment methods with potential utility for the design and implementation of resource recovery, detoxification, and/or volume-reduction systems. This study is not meant to provide detailed designs of such systems for specific waste streams; rather, it aims to provide background information that will aid subsequent systems designers in selecting relevant treatment processes.

For each potentially applicable treatment method identified, Part Two of this study addresses, in depth, the:

- Technical characteristics
- Underlying physical, chemical, and/or biological principles,
- Operating characteristics
  - Physical and chemical properties of suitable feed streams
  - Mode of operation
  - Physical and chemical properties of the output streams
- Operating experience
  - Principal current applications (including waste treatment)
  - Potential applications for treatment of hazardous wastes
- Capital and operating costs (including credits for products recovered)
- Environmental impacts
  - Waste streams or residues associated with the treatment process
  - Pollution control or further treatment requirements
- Energy requirements
  - electricity
  - fossil fuels
- Outlook for industrial waste treatment
  - current state-of-the-art
  - factors favoring and inhibiting widespread use
  - development needs

To increase the utility of the information provided on individual treatment processes, Part One of this report presents general guidelines for selecting those treatment processes which are potentially applicable to wastes of particular characteristics.

B. APPROACH

1. Literature Search

An extensive literature search on potentially useful processes was initiated. The Hazardous Waste Management Division (HWMD) of the EPA made information available from its files, and conducted a computerized search of the SWIRS (Solid Waste Information Retrieval System) data bank for pertinent articles. Prior HWMD contractor reports(1,2,3) and the Division's Report to Congress(4) were reviewed. An independent search of the general literature and patent literature was performed and trade and professional organizations and government agencies, industries, and universities were contacted.

By the time of this report, 47 treatment processes had been identified (Table 1). (Incineration and encapsulation processes are excluded, as they are the subjects of other U.S. EPA studies.) At least two processes were assigned to each of 12 ADL technical staff specialists for in-depth investigation, thus the study team was able to develop a high level of technical and professional expertise on all processes of real potential applicability to industrial wastes.

2. Interview Program

The processes identified in the Literature Search were subdivided into the five categories defined in Table 2. These categories were set up to guide the amount of effort required by the contractor for each process. A site visit and personal interview program was planned to obtain first-hand information and expert opinion or advice on the processes in each category.

In addition to hundreds of telephone contacts, each expert made two to seven site visits for each identified Category II-V process. The visits covered commercial and industrial waste treatment facilities, equipment suppliers; industrial laboratories; government laboratories; and/or experts. In all instances, each specialist gathered information for other team members as appropriate.

3. Analysis of Information

a. Mini-Reports

On the basis of the initial Literature Search, each technical specialist prepared a preliminary state-of-the-art report on his/her assigned processes. These reports, generally 5-10 pages in length, were used to help assign processes to categories (Table 2); to identify key information gaps for investigation in the Interview Program; and to report progress to date to EPA.

TABLE 1

TREATMENT PROCESSES IDENTIFIED

Physical

- Air Stripping
- Suspension Freezing
- Carbon Adsorption
- Centrifugation
- Dialysis
- Distillation
- Electrodialysis
- Electrophoresis
- Evaporation
- Filtration
- Flocculation
- Flotation
- Freeze Crystallization
- Freeze Drying
- High Gradient Magnetic Separation
- Ion Exchange
- Liquid Ion Exchange
- Steam Distillation
- Resin Adsorption
- Reverse Osmosis
- Sedimentation
- Liquid-Liquid Extracting of Organics
- Steam Stripping
- Ultrafiltration
- Zone Refining

Chemical

- Calcination and Sintering
- Catalysis
- Chlorinolysis
- Electrolysis
- Hydrolysis
- Microwave Discharge
- Neutralization
- Oxidation
- Ozonolysis
- Photolysis
- Precipitation
- Reduction

Biological

- Activated Sludge
- Aerated Lagoon
- Anaerobic Digestion
- Composting
- Enzyme Treatment
- Trickling Filter
- Waste Stabilization Pond

Pretreatment of Bulk Solids of Tars

- Crushing and Grinding
- Cryogenics
- Dissolution

TABLE 2

CATEGORIZATION OF PROCESSES BY EFFORT NEEDED

No.	Category Description	Work Effort for Each Process
I.	Process is not applicable in a useful way to wastes of interest to this program	Enough to justify category assignment
II.	Process might work in 5-10 years, but needs research effort first	Same as Category I, plus description of what questions need to be answered by future effort
III.	Process appears useful for hazardous wastes, but needs development work	Same as Category II plus description of current uses and projected applications to industrial wastes
IV.	Process is developed but not commonly used for hazardous wastes	Same as Category III
V.	Process will be common to most industrial waste processors	Description of how used, where, for what, including economics, environment, energy, etc.

b. Final Report

After an extensive field Interview Program, each Mini-Report was revised and expanded into comprehensive final treatment process reports (Part Two). The results on individual processes are summarized and compared herein.

III. TREATMENT PROCESSES INVESTIGATED

Most of the 47 processes identified in this study (Table 1) are unit processes or operations, several of which would normally have to be linked in series to form a complete treatment system for a particular waste stream. Four of the processes, however, were found to have little or no potential utility in a hazardous waste management system; that is:

- *Dialysis*, while it does separate high-molecular-weight molecules from low-molecular-weight salts, results in two output streams, both of which are more dilute than the original stream but not suitable for direct disposal.
- *Electrophoresis* could in principle be used to remove suspended colloidal matter (1-20 μ particle size) from any aqueous or organic medium, provided that the colloidal particles were charged relative to the liquid phase. However, the process is not only underdeveloped, but also unpromising. There are no scientific or practical guides upon which to base a development program, so there is some question that high removal efficiencies could be achieved. Suitable equipment is not available. Furthermore, in any working unit, electrode reactions would have to be suppressed, the conductivity of the waste stream might have to be below 300 microhms/cm, turbulent mixing would have to be avoided, and potential problems of membrane plugging would have to be solved.
- *Freeze drying* is an operationally difficult, expensive and energy-intensive dewatering process whose use would not appear to be justified in the treatment of any real waste streams.
- *Zone refining* is a slow, costly, energy-intensive process for purification of solids. It can only be operated in batch, on samples weighing less than 10 kg, which are relatively pure. It is impractical for the complex mixtures which are typical of waste streams.

Thus, of the initial 47, this left 43 as potentially useful processes to be investigated. These processes fall naturally into four classes: (1) phase separation processes, potentially useful in volume reduction or resource recovery; (2) component separation processes, capable of physically segregating particular ionic or molecular species from multicomponent, single-phase waste streams; (3) chemical transformation processes, which promote chemical reactions to detoxify, recover, or reduce the volume of specific components in waste streams; and (4) biological treatment methods, which involve chemical transformations brought about by the action of living organisms.

A. PHASE SEPARATION

Waste streams, such as slurries, sludges and emulsions, which are not single phase, will often require a phase-separation process (Table 3) before detoxification or recovery steps can be implemented. Frequently, phase separation permits a significant volume reduction, particularly if the hazardous component is present to a significant extent in only one of the phases. Furthermore, by concentrating the hazardous portion of the stream, sequential processing steps may be accomplished more readily. Phase-separation processes usually are mechanical, inexpensive and simple, and can be applied to a broad spectrum of wastes and waste components.

Emulsions are generally very difficult to separate. Heating, cooling, change of pH, salting out, centrifugation, API separators, etc., may all be tried, but there is no accurate way to predict what might work. Appropriate methods can only be developed empirically, specific to any given situation.

1. Settlable Slurries

Conceptually, the simplest separation process is *sedimentation*, or gravity settling. The output streams will consist of a sludge and a decantable supernatant liquid. If the components of the sludge are at all soluble, the supernatant liquid generally will be a solution. A closely related process and the phase separation process in most common use is *filtration*. *Centrifugation* is essentially a high gravity sedimentation process whereby centrifugal forces are used to increase the rate of particle settling. *Flotation* is used extensively in ore separation, and in fact is the single most important process that has made it possible to recover value from lower and lower grades of metallic and non-metallic ores. It has not been extensively studied for hazardous waste applications. *High-gradient magnetic separation* is a relatively new process that appears to have potential for separating magnetic and paramagnetic particles from slurries.

2. Colloidal Slurries

The basic concept in all the above processes for settable slurries is to get the solid phases to drop out of the liquid phase, through the use of gravitational, centrifugal magnetic, or hydrostatic forces. Such forces generally do not act on colloidal suspended particles.

The simplest and most commonly used colloidal separation process is flocculation. Ultrafiltration has many industrial applications, including waste treatment, and is expected to have many more within the next five years. Further development effort is required, however, to demonstrate its full potential.

TABLE 3

PHASE SEPARATION PROCESSES

	Process Category[1]	Type of Waste to Which Process Is Applicable			
		Settlable Slurries[2]	Colloidal Slurries[2]	Sludges[3]	Any Wastes With a Volatile Liquid Phase
V.	Common in Waste Treatment	Sedimentation Filtration	Flocculation	Filtration	Solar Evaporation
IV.	Developed but not commonly used in Waste Treatment	Centrifugation			Distillation (with solvent recovery) Evaporation
III.	Need further development for Waste Treatment	Flotation High-Gradient Magnetic Separation	Ultrafiltration	Freezing	

1. Described in more detail in Table 2.
2. A slurry is defined as a pumpable solid-liquid mixture. It is settlable if the phases separates on standing, and colloidal if they do not.
3. A sludge is defined as a non-pumpable solid-liquid mixture.

3. Sludges

The major phase separation desired in the handling of sludges is dewatering. Vacuum filtration or press filtration are the processes in most common use. Some research has been done on simple freezing, but the process is not well developed and the work that has been done is not promising.

4. Volatiles

Sludges and slurries (colloidal or separable) in which the liquid phase is volatile may be treated by either evaporation or distillation. Solar evaporation is very commonly used. Engineered evaporation or distillation systems would normally be operated if recovery of the liquid is desired.

B. COMPONENT SEPARATION

The many physical processes which act to segregate ionic or molecular species from multicomponent waste streams (Table 4) do not require chemical reactions to be effective. None are so commonly used as to be classified in Category V, but there has been a great deal of experience with most of them in the water treatment field. The majority of Category IV processes act only on aqueous solutions.

C. CHEMICAL TRANSFORMATION

The relatively few processes which involve chemical reactions (Table 5) are the only processes which we found are potentially capable of detoxifying hazardous components in waste streams (in addition to recovering resources or reducing volume for land disposal). By far the two most common processes are neutralization and precipitation. Since there is usually a pH range where the solubility of heavy metal precipitates is at a minimum, neutralization (interpreted broadly as pH adjustment) and precipitation are in fact often used together.

D. BIOLOGICAL TREATMENT

Biological Treatment methods (Table 6) are only effective in aqueous media, and are only capable of breaking down organic components. The four Category V processes are used essentially in polishing of soluble organics. The feed streams must be low in solids (<1%), free of oil and grease, and non-toxic to the active microorganisms (e.g., heavy metal content less than 10 ppm). The processes yield a biomass sludge for disposal which contains heavy metals and refractory organics not decomposed by the biologically active species present.

The Category IV processes, anaerobic digestion and composting, are useful for more concentrated waste streams and will tolerate solid contents of 5-7% and 50%, respectively. Composting will decompose oils, greases, and tars, yielding a concentrated metal sludge and a leachate containing partially decomposed organics.

TABLE 4

COMPONENT SEPARATION PROCESSES

		Function of Process			
	Process Category	Removal of heavy metal and toxic anions from aqueous solutions	Removal of organics from aqueous solutions	Removal of inorganics from liquids, slurries and sludges	Solvent Recovery
IV.	Developed, but not commonly used in Waste Treatment	Liquid Ion Exchange Electrodialysis Reverse Osmosis Ion Exchange	Ultrafiltration Solvent Extraction Carbon Adsorption Resin Adsorption Steam Stripping Air Stripping		Distillation Steam Distillation
III.	Needs further development for Waste Treatment			Freeze crystallization	
II.	Needs further research	Ion Flotation		High-Gradient Magnetic Separation	

TABLE 6

CHEMICAL TRANSFORMATION PROCESSES

	Process Category	Treatable Components and Waste Streams					
		Cyanides, phenolics, sulfides, sulfites, and organics in aqueous solution	Nitrates, carbonates, sulfates, hydroxides, in sludges, tars, and solids	Heavy metals in aqueous solution	Organic liquids, sludges, slurries tars and solids	Acids and Bases	Organic liquids
V.	Common in Waste Treatment			Precipitation		Neutralization	
IV.	Developed but not commonly used in Waste Treatment	Oxidation Ozonation UV/Ozonolysis UV/Chlorination	Calcination	Reduction			
III.	Requires further development for Waste Treatment			Electrolysis	Hydrolysis		Chlorinolysis
II.	Needs further research	Photolysis Catalysis		Precipitate Flotation	Catalysis		Microwave

TABLE 6

BIOLOGICAL TREATMENT METHODS

	Functions of Process	
Process Category	Decomposition of soluble organics in dilute aqueous streams	Decomposition of hydrocarbons (non-chlorinated)
V. Common in Waste Treatment	Activated sludge Aerated Lagoon Trickling Filter Waste Stabilization Pond	
IV. Developed but not commonly used in Waste Treatment		Composting Anaerobic Digestion
II. Needs further research	Enzyme Treatment	

Enzyme treatment has been shown to be effective for phenols and some hydrocarbons, but the waste stream must be of constant composition and free of inorganic contamination.

- Is the waste stream corrosive?
- Over what range will the typical physical and chemical properties vary?
- What is the volume or mass of waste that will require treatment from a typical plant and/or region?
- Where does the waste stream originate and at what points could it be intercepted for treatment?

Questions on the nature of the waste stream are asked for several reasons. One is to determine whether the waste stream characteristics match the feed stream requirements for various treatment processes. In a positive sense, this may be of interest to select processes for further consideration; or in a negative sense, to rule out processes that are not and could not be made useful for the particular waste under any circumstances. Another is to determine whether the waste stream is compatible with typical treatment process equipment, materials of construction, pumps, throughput rates, temperature, size of pipes, etc. A third, reflected in the last question, is to determine whether air and water pollution controls, or the method of waste collection used, might in fact create a stream which is more difficult to treat than the waste originally generated in the manufacturing operation.

- Objectives of Treatment – Desired Characteristics of the Output Stream
  - What is the present treatment/disposal method and why is this unacceptable?
  - What are the objectives or goals of treatment, in order of priority, i.e., purification, resource recovery, detoxification, volume reduction, safe disposal to land, safe disposal to water, compliance with regulations ?
  - What are the air, water and other environmental quality regulations which must be complied with?
  - What must be removed to make the waste stream amenable to disposal? What level of removal is necessary; i.e., what are the maximum allowable concentrations in the output stream(s)?
  - What are the chemical and physical property requirements for recycle or reuse of the output streams?
  - What are the physical and chemical property requirements for disposal to land or water?

IV. SELECTION OF TREATMENT PROCESSES FOR GIVEN WASTE STREAMS

A. PHILOSOPHY OF APPROACH

There are a variety of ways to approach the problem of selecting the appropriate process(es) for treatment of a particular waste stream. Individual engineers, chemists, equipment manufacturers, salesmen, environmental managers, plant managers, regulatory authorities, etc., will each have slightly different perspectives on the problem, different data needs, and different ways of manipulating the data to reach a final conclusion. No one approach is "right" for everyone. The sequence of steps that to one individual seems necessary and immutable, may to another seem irrelevant or illogical.

Within the scope of this report we cannot duplicate the thought processes of the many different kinds of individuals who might be involved in the selection of waste treatment alternatives. We also cannot impose our own thinking – no matter how logical it may seem to us – on individuals who approach the problem differently. To resolve this dilemma, we have chosen first to pose some of the questions to which various people might require answers before even beginning to match wastes with treatment processes. Next, we have provided a number of examples of possible steps in process selection for some typical wastes. We leave it to the individual reader to decide what questions he must have answered, and in what sequence, in order to be able to develop a procedure that meets his needs for choosing the treatment processes applicable to particular waste streams. No matter how one approaches the problem of process selection, there are two seemingly conflicting criteria to keep in mind. The first is to *eliminate inappropriate processes* from consideration *at the earliest stage feasible*. The second is to *maintain an open mind for consideration of attractive processes as long as possible.*

B. BACKGROUND QUESTIONS FOR TREATMENT PROCESS SELECTION

- Nature of the Waste
    - What are the characteristics of the waste stream?
    - Is it a liquid, an emulsion, a slurry, a sludge, a solid powder, or a bulk solid?
    - What is its chemical composition?
    - Which components are potentially hazardous for land disposal; or more generally, what is the problem?
    - What are the physical properties of the waste stream – e.g., viscosity, melting point, boiling point, vapor pressure, Btu content, specific gravity, etc.?

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- Is the waste stream corrosive?

- Over what range will the typical physical and chemical properties vary?

- What is the volume or mass of waste that will require treatment from a typical plant and/or region?

- Where does the waste stream originate and at what points could it be intercepted for treatment?

Questions on the nature of the waste stream are asked for several reasons. One is to determine whether the waste stream characteristics match the feed stream requirements for various treatment processes. In a positive sense, this may be of interest to select processes for further consideration; or in a negative sense, to rule out processes that are not and could not be made useful for the particular waste under any circumstances. Another is to determine whether the waste stream is compatible with typical treatment process equipment, materials of construction, pumps, throughput rates, temperature, size of pipes, etc. A third, reflected in the last question, is to determine whether air and water pollution controls, or the method of waste collection used, might in fact create a stream which is more difficult to treat than the waste originally generated in the manufacturing operation.

- Objectives of Treatment – Desired Characteristics of the Output Stream

  - What is the present treatment/disposal method and why is this unacceptable?

  - What are the objectives or goals of treatment, in order of priority, i.e., purification, resource recovery, detoxification, volume reduction, safe disposal to land, safe disposal to water, compliance with regulations ?

  - What are the air, water and other environmental quality regulations which must be complied with?

  - What must be removed to make the waste stream amenable to disposal? What level of removal is necessary; i.e., what are the maximum allowable concentrations in the output stream(s)?

  - What are the chemical and physical property requirements for recycle or reuse of the output streams?

  - What are the physical and chemical property requirements for disposal to land or water?

Questions on the desired characteristics of the output streams are asked to: (1) clarify the objectives of a treatment process, (2) explicitly learn what regulatory standards must be met, (3) help establish criteria for judging the usefulness of various treatment alternatives in meeting the objectives; and (4) establish a bench mark for improvement by identifying current practice.

- Technical Adequacy of Treatment Alternatives
  - What processes, alone or in combination, are capable of meeting the treatment objectives?
  - If a sequence of processes is needed, are the processes technically compatible?
  - Can the key process selected for meeting the objectives handle the waste stream in its existing form? If not, can the waste stream be put into a form amenable to the process?
  - What key processes are really attractive technically?
  - Are there any components of the waste stream that would inhibit application of an otherwise technically attractive key process? Can these potentially inhibiting effects be minimized or eliminated?
  - If no process, as presently conceived, can meet the objectives, can any process be modified to do the job?
  - What function can each process perform, and how can the processes be grouped to achieve the objectives?
  - Are there any processes that must be eliminated on technical grounds?

Questions about technical adequacy are asked to help distinguish processes that are technically feasible for use on the waste from those that are totally infeasible treatment alternatives.

- Economic Considerations
  - What are the capital investment requirements for process implementation?
  - What are the operating costs?

- To what extent will credit for recovered material help offset operating costs?

- How do projected costs for alternative treatments compare with current costs of disposal and with each other?

- If recovery was an objective, is there enough value in the potentially recoverable material to be worthwhile?

- Are the technically optimal operating parameters in the proper range for economic operation of apparently attractive processes?

- If process modifications are required, what will they cost?

- For technically and operationally acceptable processes with equal operating costs (including capital amortization), is there any economic reason to prefer the lowest capital cost alternative?

- What is the cost impact of any necessary environmental controls?

From the industry point of view, economic questions are paramount in selecting alternative treatment methods for in-plant use and in choosing a waste treatment contractor.

- Environmental Considerations

  - Will air pollution control devices be required to clean up effluents?

  - Will output streams require clean-up prior to discharge into water bodies?

  - Will secured chemical landfill areas be necessary for solid residue(s) from process?

Waste treatment processes, like any manufacturing process, almost always result in some residue for disposal. Environmental questions are directed towards tracing the fate of the hazardous components present in the waste feed stream to the point of ultimate disposal.

- Energy Considerations

  - What are the energy requirements for process operation?

  - What form(s) of energy will be used, i.e., electricity, natural gas, oil, coal, etc.?

- Are estimated energy costs more than 10% of operating costs?

Questions of energy utilization are asked in order to assure that treatment processes satisfy current national objectives of both environmental protection and energy conservation. Both the absolute quantity of energy required and the form of the energy required are important. Energy-intensive processes generally would be in disfavor, unless there are compensating benefits (e.g., materials recovery). Processes that use natural gas, which is in short supply, might be particularly unattractive. The economics of treatment processes for which energy costs represent a significant fraction of operating costs would, of course, be tied to the price of fuel, which has in the recent past been quite volatile.

- Overall Evaluation
  - What factors are most important in selecting a treatment process?
  - Are there any standard, state-of-the-art processes that can be used for baseline comparisons?
  - Are costs "reasonable"?
  - Does any process have clearly desirable (or undesirable) features that make it attractive (or unattractive) for treating a particular waste stream?

The final choice of a treatment system, or treatment process sequence, for a given waste stream involves engineering judgment, which is always highly subjective. The individual faced with the choice must not only establish his/her own selection criteria, but also weight those criteria in accordance with personal priorities. Questions asked in an attempt to make an overall evaluation, therefore, are directed towards a determination of the degree to which the objective features of alternative treatment systems meet subjective needs.

C. EXAMPLES OF PROCESS SELECTION PROCEDURES

1. Selection Based on the Nature of the Hazardous Wastes

For the purposes of identifying possible treatment processes, and eliminating those that are not likely to prove useful, a given waste stream is conveniently characterized with respect to three broad dimensions:

(a) *Physical form* – Is the waste stream as generated a:

- liquid?
- emulsion?
- pumpable slurry?

  - colloidal or non-colloidal?
- non-pumpable sludge?
- tar?
- bulk solid?
- powdered solid?

(b) *Hazardous components* – Does the waste stream contain:

- heavy "metal" cations (Sb, As, Cd, Cr, Hg, Pb, Zn, Ni, Cu, V, P, Be, Se, Mn, Ti, Sn, Ba, etc.)?
- heavy metal anions (chromates, chromites, arsenates, arsenites, etc.)?
- non-metallic toxic anions (cyanides, sulfites, thiocyanates, etc.)?
- organics (hydrocarbons, organic acids, organic peroxides, esters, alcohols, aldehydes, phenols, chlorocarbons, amines, anilines, pyridines, organic sulfur compounds, organic phosphorus compounds, alkaloids, sterols, etc.)?

(c) *Other properties* – For example,

- Is the liquid phase primarily aqueous or non-aqueous?
- What is the concentration of each of the hazardous components in each of the phases present?
- What are the non-hazardous components in each phase?

For a given waste stream, characterized by physical form and hazardous components, the matrix presented in Table 7 may be used to select potentially applicable treatment processes. For example, liquid ion exchange (LIE) might be capable of removing heavy metals from solid powders. The matrix in Table 8 focusses on processes that are *inapplicable* for given waste streams. It provides some guidance for ruling out processes that are not likely to be technically feasible for certain types of waste streams.

2. Process Selection Based on Desired Characteristics of the Output Streams

The output streams from any given treatment process may or may not be suitable for reuse or amenable to disposal without further treatment. In evaluating and analyzing treatment processes that might be applicable to particular waste streams, it is usually necessary at some stage to define the objectives of treatment and the desired characteristics of the output streams.

TABLE 7

TREATMENT PROCESSES FOR HAZARDOUS COMPONENTS IN WASTE STREAMS OF VARIOUS PHYSICAL FORMS

Physical Form	Treatment Processes*		
	Heavy "metal" cations* and metal anions**	Non-metal anions***	Organics
Liquid	(IE), (FC), (UF), (ED), (RO), (Red), (LIE), (Ppt), (E1)	(CA), (LIE), (FC), (UF), (ED), (Oz), (RO), (Ox), (E1)	(CA), (RA), (Dis), (IE), (AS), (SS), (UF), (SE), (RO), (Ox), (Oz), (Hy), (C1), (MW), (Pb), (UF)
Emulsion	(UF)		
Slurry	(FC), (UF), (Red), (HGMS)	(FC), (UF), (Ox)	(Dis), (AS), (SS), (UF), (Oz), (Hy)
Sludge	(LIE), (FC), (Red)	(FC), (Ox)	(Dis), (Cal), (Oz), (Hy), (Ox)
Tar	(Cal)	(Cal)	(Cal), (Hy)
Bulk Solid	(Cal)	(Cal)	(Cal)
Solid Powder	(LIE)	(Cal)	(Cal), (Hy)

Legend:

(AS)	Air Stripping	(HGMS)	High-Gradient Magnetic Separation	(Ppt)	Precipitation
(CA)	Carbon Adsorption	(Hy)	Hydrolysis	(RA)	Resin Adsorption
(Cal)	Calcination	(IE)	Ion Exchange	(Red)	Reduction
(C1)	Chlorinolysis	(LIE)	Liquid Ion Exchange	(RO)	Reverse Osmosis
(Dis)	Distillation	(MW)	Microwave Discharge	(SE)	Solvent Extraction
(ED)	Electrodialysis	(Ox)	Oxidation	(SS)	Steam Stripping
(E1)	Electrolysis	(Oz)	Ozonation	(UF)	Ultrafiltration
(FC)	Freeze Crystallization	(Ph)	Photolysis		

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*e.g., Sb, As, Cd, Cr, Hg, Pb, Zn, Ni, Co, V, P,Be, Se, Mn, Ti, Sn, Ba

**e.g., chromates, arsenates, arsenites, vanadates

***e.g., cyanides, sulfides, fluorides, hypochlorites, thiocyanates

TABLE 8

APPLICABILITY OF TREATMENT PROCESSES TO PHYSICAL FORM OF WASTE

	Single Phase				Two Phases	
		Liquid				
	Solid	Inorganic	Organic	Mixed	Slurry*	Sludge
1. Phase Separation Processes						
Filtration	n	n	n	n	y	n
Sedimentation	n	n	n	n	y	n
Flocculation	n	n	n	n	n	n
Centrifugation	n	n	n	n	y	n
Distillation	n	n	n	n	y	y
Evaporation	n	n	n	n	y	y
Flotation	n	n	n	n	y	n
Ultrafiltration	n	n	n	n	n	n
HGMS	p	n	n	n	n	n
Precipitation	n	n	n	n	n	n
2. Component Separation Processes						
Ion Exchange	n	y	y	y	n	n
Liquid Ion Exchange	y	y	y	n	y	y
Freeze Crystallization	n	y	y	n	y	y
Reverse Osmosis	n	y	n	y	n	n
Carbon Adsorption	n	y	n	y	n	n
Resin Adsorption	n	y	n	y	n	n
Electrodialysis	n	y	n	y	n	n
Air Stripping	n	n	y	y	y	n
Steam Stripping	y	n	y	y	y	n
Ammonia Stripping.	y	y	n	n	n	n
Ultrafiltration	n	y	y	y	n	n
Solvent Extraction	p	y	y	y	n	n
Reverse Osmosis	n	y	n	y	n	n
Distillation	n	n	y	y	y	y
Evaporation	n	y	y	y	y	y
3. Chemical Transformation Processes						
Neutralization	n	y	y	y	y	y
Precipitation	n	y	y	y	n	n
Hydrolysis	p	n	y	y	y	y
Oxidation	n	y	y	y	n	n
Reduction	n	y	y	y	n	n
Ozonolysis	n	y	y	y	n	n
Calcination	y	y	y	y	y	y
Chlorinolysis	n	n	y	y	n	n
Electrolysis	n	y	n	y	n	n
Microwave	n	n	y	y	n	n
Biological	n	n	y	y	y	y
Catalysis	n	y	y	y	n	n
Photolysis	n	n	y	y	n	n

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*Slurry is defined here as a pumpable mixture of solids and liquids.

y = yes, workable; n = no; p = possible.

For example, if the treatment objective is to convert the given waste stream to one or more streams which can legally be discharged to a water body, the Federal and local water pollution control regulations will govern the characteristics of the output streams. If the treatment objective is recovery, those processes must be sought which either lead directly to a reusable resource, or which convert the waste to a form from which resources may be more easily recovered.

Table 9 provides some general characteristics of the output streams (end products) from various processes to aid in assessing their capability, alone or in combination, to meet defined objectives. Where processes are routinely or conveniently used in combination, follow-on steps are suggested, predicated on the assumption that the only hazardous components in the waste stream are those that the process listed can act on. If, for example, a waste stream containing both low-molecular-weight organic and heavy metal contaminants were treated by reverse osmosis, only the heavy metals would be concentrated in one of the output streams (RO1), and the other output stream (RO2) would have to be treated further to remove or detoxify the organics.

3. Selection Based on Technical and Operational Adequacy of Treatment Alternative

Table 7 shows that there are a number of treatment alternatives for various types of hazardous components in waste streams of different physical form. Tables 4-6 show further that several of the alternatives function similarly; i.e., they remove or detoxify certain types of hazardous components. All processes which function similarly on similar types of waste streams are not necessarily technically equivalent, however. The allowable feed stream concentrations may differ. The treatment efficiencies and hence concentration of hazardous components in the output streams may differ. The degree of interference by other components in the waste stream may differ. Throughputs may differ and the available experience with using the processes to treat hazardous wastes may also differ.

Table 10 compares treatment processes capable of separating heavy metals from liquid waste streams with respect to feed stream properties, output parameters and state-of-the-art. Tables 11-13 provide similar comparisons for processes that separate organics from liquids and toxic anions from liquids. Table 14 compares processes (other than phase separation processes) that can accept feed streams in the form of slurries or sludges. Table 15 compares processes that can accept feed streams in the form of tars, bulk solids or solid powders.

It is clear that the vast majority of processes considered in this program operate mainly on liquids. Some have potential for handling slurries and sludges, but in most real cases, a liquid/solid separation would precede treatment and/or disposal. None of the processes can directly treat bulk solids contaminated by heavy metals, such as slags from the metallurgical industries (an enormously large waste stream in the aggregate). Few processes can work directly on tarry or even powdered solid feeds. Unfortunately, water treatment sludges, still bottom tars, powdered particulate from air pollution control devices and oil-contaminated solids account for a larger fraction of the wastes destined for land disposal than do liquids.

TABLE 9

GENERAL CHARACTERISTICS OF THE END-PRODUCTS OF TREATMENT PROCESSES

Treatment		Output Streams			Possible Follow-On Steps
Type	Process	Code No.	Form	Characteristics	
1. Phase Separation	Filtration	F 1	Sludge	15-20% solids	Landfill, Calcination
		F 2	Liquid	500-5000 ppm total dissolved solids	Component Separation
	Sedimentation	S 1	Sludge	2-15% solids	Decantation
	Centrifugation	S 2	Liquid	10-200 ppm suspended solids	
	Flotation	Fl 1	Stabilized	particle-bearing froth	Skimming
		Fl 2	Liquid	solution	Component Separation
	HGMS	H 1	Slurry	magnetic and paramagnetic particles	Recovery
		H 2	Liquid	solution	Component Separation
	Flocculation	Fc	Sludge or Slurry	flocculated particulates	Sedimentation, Filtration, Centrifugation
	Distillation	Dis 1	Sludge	still bottoms	Calcination
		Dis 2	Liquid	pure solvent	Sale
	Evaporation	E 1	Solid	–	Resource Recovery
			Liquid	condensate	Recovery or Disposal
2. Component Separation					
a. Inorganics	Ion Exchange	IE 1	Liquid	concentrated solution of hazardous components	Precipitation, Recycle, Electrolysis
		IE 2	Liquid	purified water with hazardous components at ppm levels	Discharge
	Liquid Ion Exchange	Similar to Ion Exchange			
	Carbon Adsorption	CA 1	Solid	adsorbate on carbon	Chemical Regeneration
		CA 2	Liquid	purified water	Discharge
	Reverse Osmosis	RO 1	Liquid	concentrated solution of hazardous components	Precipitation, Electrolysis, Recycle
		RO 2	Liquid	purified solution, TDS > 5 ppm	To Water Treatment

TABLE 9 (Continued)

Treatment		Output Streams			Possible Follow-On Steps
Type	Process	Code No.	Form	Characteristics	
	Electrodialysis	ED 1	Liquid	concentrated stream, 100-600 ppm salts	Precipitation, Metal Recovery
		ED 2	Liquid	dilute stream	To Water Treatment
	Freeze Crystallization	FC 1	Sludge	concentrated brine	Recovery
		FC 2	Liquid	purified stream, ~ 100 TDS	To Water Treatment
b. Organics	Carbon Adsorption	CA 1	Solid	adsorbate on carbon	Thermal or Chemical Regeneration
		CA 2	Liquid	purified water	Discharge
	Resin Adsorption	RA 1	Solid	adsorbate on resin	Solvent Regeneration
			Liquid	purified water, < 10 ppm organics	To Water Treatment
	Steam Stripping	SS 1	Liquid	aqueous steam concentrated in volatile organics	Recovery; Incineration
			Liquid	dilute aqueous stream with 50-100 ppm organics	To Water Treatment
	Solvent Extraction	SE 1	Liquid	concentrated solution of hazardous components in extraction solvent	Recovery of Extraction Solvent
		SE 2	Liquid	purified liquid; hazardous component concentration < 10 ppm	Recycle or Discharge
	Distillation	Dis 1	Sludge	still bottoms	Incineration
		Dis 2	Liquid	pure liquid	Sale
3. Chemical Transformation					
	Neutralization	N	Unchanged	stream of altered pH	Component Separation
	Precipitation	Ppt 1	Sludge	—	Landfill, Calcination
		Ppt 2	Liquid	supernatant with concentrations governed by solubility of precipitate	Depends on Product Stream Composition
	Oxidation Ozonation	O	Liquid	CO_2, H_2O and other oxidation products	Depends on Product Stream Composition
	Reduction	R	Slurry	heavy metals and residual reducing agent	Filtration

TABLE 9 (Continued)

Treatment		Output Streams			Possible Follow-On Stream
Type	Process	Code No.	Form	Characteristics	
	Calcination	Cal 1	Solid	oxide and/or other residue	Landfill or Recovery
		Cal 2	Gas	volatiles (CO_2, NO_x, SO_x, hydrocarbons, fine particulates)	Wet Scrubbing
	Hydrolysis	Hy	Liquid, Slurry or Sludge	mixture of products that may or may not be toxic	Resource Recovery
	Electrolysis	El 1	—	cathode reaction products	Often a Recovered Metal
		El 2	—	anode reaction products	Depends on Nature of Products
	Photolysis	P	Liquid	solution of photodecomposition products	Depends on Nature of Products
	Microwave Discharge	M	Gas	similar to incinerator emissions	Wet Scrubbing
	Catalysis	Depends on Reaction Catalyzed			
4. Biological Treatment					
	Activated Sludge	AC 1	Liquid	clean water	Discharge
		AC 2	Sludge	heavy metals and refractory organics	Calcination
	Aerated Lagoon				
	Trickling Filter				
	Waste Stabilization Pond	W	Liquid	clear water	Discharge
	Anaerobic Digestion	An 1	Sludge	—	Incineration
		An 2	Gas	CO_2, methane	Fuel Recovery
	Composting	Com 1	Sludge	concentrated in metals	Calcination or Recovery
		Com 2	Liquid	leachate solution of partially degraded organics	Component Separation

TABLE 10

COMPARISON OF PROCESSES THAT SEPARATE HEAVY METALS FROM LIQUID WASTE STREAMS

Process	State-of-the-Art	Required Feed Stream Properties	Characteristics of Output Stream(s)
Physical Removal			
Ion Exchange	Used but not common (Cat. IV)	Con. < 4000 ppm; aqueous solutions, low SS	One concentrated in heavy metals; one purified
Reverse Osmosis	Cat. IV	Con. > 400 ppm; aqueous solutions; controlled pH; low SS; no strong oxidants	One concentrated in heavy metals; one with heavy metal concentrations > 5 ppm
Electrodialysis	Cat. IV	Aqueous solutions; neutral or slightly acidic; Fe and Mn < 0.3 ppm; Cu < 400 ppm	One with 1000-5000 ppm heavy metals; one with 100-500 ppm heavy metals
Liquid Ion Exchange	Cat. IV	Aqueous solutions; no concentration limits; no surfactants; SS $< 0.1\%$	Extraction solvent concentrated in heavy metals; purified water or slurry
Freeze Crystallization	Needs development (Cat. III)	Aqueous solutions; TDS $< 10\%$	Concentrated brine or sludge; purified water, TDS ~ 100 ppm
Chemical Removal			
Precipitation	Common (Cat. V)	Aqueous or low viscosity non-aqueous solutions; no concentration limits	Precipitated heavy metal sulfides, hydroxides, oxides, etc.; solvent with TDS governed by solubility product of precipitates
Reduction	Cat. IV	Aqueous solutions; concentrations of heavy metals $< 1\%$; controlled pH	Acidic solutions with reagent (oxidized $NaBH_4$ or Zn); metallic precipitates
Electrolysis	Cat. III	Aqueous solutions; heavy metal concentrations $< 10\%$	Recovered metals; solution with 2-10 ppm heavy metals

TABLE 11

COMPARISON OF TREATMENT PROCESSES THAT SEPARATE ORGANICS FROM LIQUID WASTE STREAMS

Treatment Process	State-of-the-Art	Required Feed Stream Properties	Characteristics of Output Stream(s)
Carbon Adsorption	Used but not common (Cat. IV)	Aqueous solutions; concentrations $< 1\%$; SS < 50 ppm	Adsorbate on carbon; usually regenerated thermally or chemically
Resin Adsorption	Cat. IV	Aqueous solutions; concentrations $< 8\%$; SS < 50 ppm; no oxidants	Adsorbate on resin; always chemically regenerated
Ultrafiltration	Cat. IV	Solution or colloidal suspension of high molecular weight organics	One concentrated in high molecular weight organics; one containing dissolved ions
Air Stripping	Cat. IV	Solution continuing ammonia; high pH	Ammonia vapor in air
Steam Stripping	Cat. IV	Aqueous solutions of volatile organics	Concentrated aqueous streams with volatile organics and dilute stream with residuals
Solvent Extraction	Cat. IV	Aqueous or non-aqueous solutions; concentration $< 10\%$	Concentrated solution of organics in extraction solvent
Distillation	Cat. IV	Aqueous or non-aqueous solutions; high organic concentrations	Recovered solvent; still bottom liquids, sludges and tars
Steam Distillation	Cat. IV	Volatile organics, non-reactive with water or steam	Recovered volatiles plus condensed steam with traces of volatiles

TABLE 12

PROCESSES THAT DESTROY ORGANICS

Process	State-of-the-Art	Required Feed Stream Properties	Characteristics of Output Stream(s)
Biodegradation	Cat. V	Dilute aqueous streams with soluble organics	Pure water
Oxidation	Cat. IV	Dilute aquebus solutions of phenols, organic sulfur compounds, chlorinated hydrocarbons, etc.	Oxidation products in aqueous solutions
Ozonation	Cat. IV	Aqueous solutions; concentrations $< 1\%$	Oxidation products in aqueous solutions
Calcination	Cat. IV	Organics and inorganics that decompose thermally	Solid oxides; volatile emissions
Hydrolysis	Needs development (Cat. III)	Aqueous or non-aqueous streams; no concentration limits	Hydrolysis products
Photolysis	Needs research (Cat. II)	Aqueous streams; transparent to light; components that absorb radiation	Photolysis products
Chlorinolysis	Cat. III	Chlorinated hydrocarbon waste streams; low sulfur; low oxygen; can contain benzene and other aromatics; no solids; no tars	Carbon tetrachloride; HCl and phosgene
Microwave Discharge	Cat. II	Organic liquids or vapors	Discharge products; not accurately predictable

TABLE 13

COMPARISON OF PROCESSES THAT SEPARATE TOXIC ANIONS FROM LIQUID WASTE STREAMS

Process	State-of-the-Art	Required Feed Stream Properties	Characteristics of Output Stream(s)
Physical Removal			
Ion Exchange	Cat. IV	Inorganic or organic anions in aqueous solution	Concentrated aqueous solutions
Liquid Ion Exchange	Cat. IV	Inorganic or organic anions in aqueous solution	Concentrated solutions in extraction solvent
Electrodialysis	Cat. IV	Aqueous stream with 1000-5000 ppm inorganic salts; and pH; Fe and Mn < 0.3 ppm	Concentrated aqueous stream (10,000 ppm salts); dilute stream (100-500 ppm salts)
Reverse Osmosis	Cat. IV	Aqueous solutions with up to 34,000 ppm total dissolved solids	Dilute solution (~ 5 ppm TDS); concentrated solution of hazardous components
Freeze Crystallization	Needs development (Cat. III)	Aqueous salt solutions	Purified water; concentrated brine
Chemical Removal			
Oxidation	Cat. III–IV	Aqueous solutions of cyanides, sulfides, sulfites etc.; concentrations $< 1\%$	Oxidation products
Ozonation	Cat. IV	Aqueous solutions of cyanides; concentrations $< 1\%$	Cyanate solutions
Electrolysis	Cat. III	Alkaline aqueous solutions of cyanides or concentrated HCl solutions ($>20\%$)	Cyanides to ammonium and carbonate salt solutions; HCl to Cl_2 gas

TABLE 14

COMPARISON OF PROCESSES THAT CAN ACCEPT SLURRIES OR SLUDGES

Process	State-of-the-Art	Required Feed Stream Properties	Characteristics of Output Stream(s)
Calcination	Used but not common (Cat. IV)	Waste stream with components that decompose by volatilization (hydroxides, carbonates, nitrates, sulfites, sulfates)	Solid greatly reduced in volume; volatiles
Freeze Crystallization	Needs development (Cat. III)	Low-viscosity aqueous slurry or sludge	Brine sludge; purified water
HGMS	Needs research (Cat. II)	Magnetic or paramagnetic particles in slurry	Particles adsorbed on magnetic filter
Liquid Ion Exchange	Cat. IV	Solvent extractable inorganic component	Solution in extraction solvent
Flotation	Cat. III	Flotable particles in slurry	Froth
Hydrolysis	Cat. II	Hydrolyzable component	Hydrolysis products
Anaerobic Digestion	Cat. IV	Aqueous slurry; $< 7\%$ solids; no oils or greases; no aromatics or long chain hydrocarbons	Sludges; methane and CO_2
Composting	Cat. IV	Aqueous sludge; $< 50\%$ solids	Sludge; leachate
Steam Distillation	Cat. IV	Sludge or slurry with volatile organics	Volatile, solid residue
Solvent Extraction	Cat. IV	Solvent extractable organic	Solution of extracted components; residual sludge

TABLE 15

COMPARISON OF PROCESSES THAT CAN ACCEPT TARS OR SOLIDS

Process	State-of-the-Art	Required Feed Stream Properties	Characteristics of Output Stream(s)
Calcination	Used but not common (Cat. IV)	Tars or solids that can be volatilized	Volatiles; char and/or metal oxides
Hydrolysis	Needs development (Cat. III)	Tars or solid powders	Hydrolysis products
Steam Distillation	Cat. IV	Solids contaminated with volatile organics	Purified solids; condensed organics
Dissolution	Cat. IV	Tars, solids, or solid powders that will dissolve in some reagent	Liquid solution for further treatment; solid residue
Crushing and Grinding	Cat. IV	Bulk solid	Powdered solid
Cryogenics	Needs research (Cat. II)	Tar, bulk solid	Reduced particle size

Crushing and grinding, and dissolution are therefore likely to play important roles in subsequent design of alternative hazardous waste treatment systems. Tars, which are often neither easy to crush and grind nor to dissolve, might be reduced to smaller particle size by cryogenic cooling. The smaller particles thus formed should dissolve more rapidly than the bulk tar removed from the reactor.

4. Selection on the Basis of Economic Considerations

Processes performing similar functions are compared with respect to capital and operating costs in Table 16. The bases for the cost estimates are summarized in the Preface to Part Two. For more detailed descriptions of the types of waste streams assumed in developing the costs in Table 15, refer to the individual process reports. In deriving costs of alternative treatment systems (generally a sequence of processes) for any given waste stream, operating parameters specific to the particular situation should be taken into account: the costs in Table 16 and the economic analyses given in Part Two only provide general guidelines.

TABLE 16

APPROXIMATE TREATMENT COSTS

Process	Annual Volume or Mass of Waste Stream Treated (typical), gpd	Capital Costs	Operating Costs	Fraction of Operating Costs Attributable to: Labor	Energy	Materials	Other*
Phase Separation							
Sedimentation	6,000,000	–	$0.10-0.60/1000 gal	–	–	–	–
Vacuum Filtration	36,000	$ 200,000	$5-7/1000 gal	46	4	1	50
Centrifugation	36,000	$ 140,000	$5-7/1000 gal	36	6	17	43
Freeze Crystallization	60,000	$ 280,000	$6-12/1000 gal	62	16	–	32
Evaporation	20,000,000	$1,300,000	$1-2/1000 gal	3	92	–	6
Metal Removal From Liquids							
Precipitation	400,000	$ 300,000	$1-2/1000 gal	47	2	5	46
Electrodialysis	9,000	$ 24,000	$5-7/1000 gal	62	3	7	28
Ion Exchange	80,000	$ 400,000	$4-6/1000 gal	36	2	46	16
Liquid Ion Exchange	80,000	$ 300,000	$3-5/1000 gal	24	1	12	63
Reduction	2,000	$ 230,000	$150-200/1000 gal	32	21	15	32
Reverse Osmosis	3,000	$ 12,000	$9-11/1000 gal	29	6	–	65
Electrolysis	20,000	$ 31,000	$1-2/1000 gal	–	10-35	–	–
Organic Removal From Liquids							
Carbon Adsorption	100,000	$1,200,000	$5-20/1000 gal (high figure with regeneration)	24	5-25 (high with thermal regeneration)	15	36-56
Resin Adsorption	67,000	$ 720,000	$11-13/1000 gal	11	40	Regenerating Solvent recovered	
Solvent Extraction	100,000	$ 400,000	$4-6/1000 gal				
Steam Stripping	720,000	$ 500,000-860,000	~$10	2	72	–	21
Steam Distillation	750	$ 130,000	$0.25-0.90/1000 gal	53	6	–	41
Distillation	1,000	$ 230,000	$264/1000 gal	14	12	–	74
Hydrolysis	30,000	$ 320,000	$20-30/1000 gal	57	17	–	26
Oxidation	1,000	$ 100,000	$229/1000 gal	44	4	15	37
Ozonation	800,000	$ 330,000	$0.40-1.00/1000 gal	26	20	–	54
Other							
Neutralization	1,000,000	$1,060,000	$2-3/1000 gal	15	1.5	59	24.5
Calcination	156,000	$2,900,000	$16-20/1000 gal	10	26	–	64
Chlorinolysis	20,000	$5,500,000	$3000/1000 gal	1	4	88	7

*Capital amortization, water, maintenance, etc.

V. WASTE TREATMENT PROCESS SUMMARIES

The following pages summarize briefly the salient features of each of the treatment process considered. More complete process descriptions are provided in Part Two.

ADSORPTION, CARBON

I. CONCLUSIONS AND RECOMMENDATIONS

Carbon adsorption should be given serious consideration whenever it is desirable to remove mixed organics, or to recover select organic or inorganic species from aqueous waste streams with adsorbate concentrations less than 1%.

II. PROCESS DESCRIPTION

A large variety of organic solutes, and a more limited number of inorganic solutes can be removed from aqueous waste streams by adsorption onto activated carbons with a high absorptive surface area (500-1500 m^2/g). Adsorption of organic solutes is commonly followed by thermal regeneration of the carbon and simultaneous destruction of the absorbates. In a few cases, the carbon may be regenerated and the adsorbate recovered by treatment with acid, base, steam, or solvent.

III. APPLICATIONS TO DATE

There are about 100 full-scale carbon adsorption systems currently in use for industrial/municipal wastewater treatment. In general, the process works best with chemicals that have a low water solubility, high molecular weight, low polarity, and low degree of ionization. The concentration of adsorbates in the influent should be less than 1%, and suspended solids must be low ($\lesssim$50 ppm) for most systems. Recovery is possible if the adsorbate may be easily volatilized or dissolved off the carbon. Thermal regeneration (with organic adsorbates) is economical if the carbon usage is above about 1000 lb/day.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements include electricity for pumps and fuel for the regeneration furnace. Energy costs may be around 25% (or higher) of the total operating costs where concentrated waste streams are being treated and the carbon is thermally regenerated. Energy may constitute no more than 5% of total operating costs if regeneration is accomplished by non-thermal means.

Capital costs for a 100,000-gpd facility would be in the neighborhood of \$1,000,000. Total operating costs would be in the range of \$5-20/1000 gal.

If spent carbon is not regenerated, it presents a problem for disposal. If it is thermally regenerated, the regeneration furnace will usually require an afterburner, a scrubber, and perhaps a dust filter.

V. OUTLOOK FOR WASTES

For aqueous waste streams containing up to 1% of refractory or toxic organics, carbon adsorption is an excellent, proven process. For more concentrated waste streams, solute removal would be even more efficient, but the more frequent regeneration required would significantly increase costs. Development of new methods of regeneration, particularly ones that allow recovery of the adsorbate, could greatly expand potential applications of the process.

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ADSORPTION, RESIN

I. CONCLUSIONS AND RECOMMENDATIONS

Resin adsorption, like carbon adsorption, is a useful process for extraction of organic solutes from aqueous waste streams. Resin adsorption will generally be preferred when it is desirable to recover the adsorbate. Carbons are usually thermally regenerated with destruction of the adsorbate. Resins are always chemically regenerated (with caustic or organic solvents).

II. PROCESS DESCRIPTION

Resin adsorption uses synthetic resins (which can vary significantly in their chemical and physical nature) to extract and recover, if desired, dissolved organic solutes from aqueous waste streams. Resins with either (or mixed) hydrophobic or hydrophylic natures are available, and can be used to extract, respectively, hydrophobic or hydrophylic solutes. Resins are always chemically regenerated. When organic solvents are used as the regenerant, solute recovery is generally via distillation.

III. APPLICATIONS TO DATE

Current industrial waste treatment applications include: phenol recovery; color removal; and fat removal from aqueous waste streams. The phenol concentration can be as high as 8% by weight in the feed.

Proposed waste treatment applications (near-term) include removal of toxic chemicals from munitions facilities' effluents; removal of pesticides from aqueous streams; carcinogen removal from laboratory waste waters; and removal of phenolics; and removal of chlorinated hydrocarbons.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements are small when the regenerant is not recycled. When both solvent and solute are recovered, the steam requirements for distillation (up to three stills required) will be significant. If the regenerant is not recycled, it must be disposed of. If the regenerant is recycled (e.g., by distillation), the still bottoms must be disposed.

Capital costs are moderately large; while no furnace is needed for regeneration (an expensive item with carbon systems), resins costs are high. Operating costs may be below $1/1000 gal in some applications, but may reach $5-20/100 gal when concentrated waste streams are treated and the solute recovered. Credit for recovered solute can allow a system to operate at a profit in favorable cases.

V. OUTLOOK FOR WASTES

Resin adsorption is particularly attractive for removing organics from aqueous waste streams when material recovery is desirable, and when the waste stream contains high levels of dissolved inorganic salts. Applications appear to be expanding.

BIOLOGICAL TREATMENT: ACTIVATED SLUDGE

I. CONCLUSIONS AND RECOMMENDATIONS

Activated sludge treatment is extensively used in industry, and is probably the most cost-effective method of destroying organics present in an aqueous waste stream. Neutralization and equalization of the waste stream, as well as suspended solids removal, should precede the activated sludge system. It is a safe and reliable process which is relatively uncomplicated to operate and relatively inexpensive. Improved understanding of activated sludge microbiology and enzyme catalysis will improve process operating efficiencies in the future.

II. PROCESS

Aqueous organic waste streams having less than 1% suspended solids have flocculated, biological growths continuously circulated and contacted in the presence of oxygen. Since the process was introduced at the turn of the century it has been modified through improved methods of maintaining aerobic conditions under varying organic loadings.

The process involves an aeration step, followed by solids-liquid separation, with recycle of a portion of the solids. The basic system has an open tank for the mixture of the active biomass with influent wastewater and air, followed by a clarifier. Bacteria in activated sludge systems serve to perform hydrolysis and oxidation reactions.

III. APPLICATIONS TO DATE

The activated sludge process has been applied extensively to treat wastewater from municipal sewage plants, canneries, paper and pulp mills, refineries, breweries, and steel, textile, petrochemical, pharmaceutical, and timber processing plants. It has also been applied to photo processing wastes and to the propylene glycol wastewater from polyvinyl chloride production.

IV. ENERGY, ENVIRONMENT, ECONOMICS

The activated sludge system is energy-intensive, with over 10% of total operating cost based on energy needed for pumping, aeration and clarification. The system is basically environmentally sound; no chemicals are added and natural degradation takes place.

Capital costs are about 10¢ per 1,000 gallons for a 10 mgd facility. These costs increase to over $1 for facilities handling less than 1 mgd. Processes handling dilute wastewaters are reported to have total costs of 10-40¢ per 1,000 gallons.

V. OUTLOOK FOR WASTES

Activated sludge systems are employed in at least two facilities for treatment of hazardous wastes. The system is environmentally sound because it employs natural microbial metabolic processes; no chemicals are added.

BIOLOGICAL TREATMENT: AERATED LAGOONS

I. CONCLUSIONS AND RECOMMENDATIONS

The aerated lagoon biological treatment process decomposes organics in wastewater containing less than 1% solids, employing essentially the same microbial reactions as activated sludge. The aerated lagoon, however, does not have a sludge recycle system for continuous circulation of microorganisms, and microbial strains do not acclimatize to the same extent. BOD removal efficiencies range from 60 to 90%. The process is not as attractive for industrial waste treatment as the activated sludge process; removal efficiencies are not as high and the process is less flexible in maintaining effluent limitations under varied influent loading.

II. PROCESS

The aerated lagoon technique developed from adding artificial aeration to existing waste stabilization ponds. Usually the lagoon is an earthen basin with sloping sides and about 6-17 feet depth. For the treatment of industrial wastes, it may be necessary to line the basin with an impermeable material. Because wastewaters in aerated lagoons are generally not as well mixed as those in activated sludge basins, a low level of suspended solids is maintained. If mixing and aeration are not complete, a portion of the solids settles to the bottom and undergoes anaerobic microbial decomposition. Retention times are slightly longer than for activated sludge; and where anaerobic decomposition is encouraged, the time is even longer.

III. APPLICATIONS TO DATE

The process has been successfully used for petrochemical, textile, pulp and paper mill, cannery, and refinery wastewaters.

IV. ENERGY, ENVIRONMENT, ECONOMICS

For comparable treatment efficiency, energy requirements are comparable to those for activated sludge treatment; but generally the aerated lagoon employs less energy for aeration and longer retention periods. Chemical requirements are essentially limited to addition of nutrients. As in activated sludge treatment, the effluent is a clarified liquid and a biomass sludge residue; the biosolids are more difficult to flocculate and settle from the mixed liquor because of the longer retention time.

Total costs range from 10 to 30¢/1000 gallons of dilute influent; if basin lining and high aeration is required, treatment costs may be nearly $2/1000 gallons.

V. OUTLOOK FOR WASTES

The process is not as attractive as activated sludge treatment for a wastewater influent with highly variable organic and metal concentrations.

BIOLOGICAL TREATMENT: ANAEROBIC DIGESTION

I. CONCLUSIONS AND RECOMMENDATIONS

Anaerobic digestion is a biological treatment process for the degradation of simple organics in an air-free environment. Part of the carbon substrate is used for cell growth and the other is converted to methane and carbon dioxide gas. The microbiology is complex and still not well understood. Two types of interdependent organisms are present, and steady-state environmental conditions must be maintained to keep them balanced. Because of this delicate balance, the process is not suitable for treatment of most industrial processing sludges. Oil, fat, and grease are also troublesome.

II. PROCESS

The organic sludges and biomass sludges from primary clarification and biological treatment are processed to reduce their volume and improve their stability. In the conventional process, the waste stream is fed into the middle zone of a closed tank with no agitating mechanism. The solids are digested by the organisms, gas rises, bringing scum to the surface, and the gas is collected from the roof of the tank. Usually this gas is used to maintain the temperature of the installation and sometimes to heat other parts of the plant. The digested sludge settles to the bottom of the tank after 30 to 60 days. There is only a small volume of digested sludge, which is stable and inert and can be disposed of for land reclamation or by ocean dumping. The bacteria are sensitive to pH, temperature, and the composition of the waste, but usually with time the system will achieve its own balance. Modifications have been made for some installations, usually involving agitation or heating, shortening the process to several days to two weeks.

III. APPLICATIONS TO DATE

Most installations have been for the digestion of sewage sludge, as the final step in a complete municipal waste treatment facility. Boston and Chicago both use anaerobic digesters: Boston disposes of the waste by ocean dumping; Chicago, whose plant is the world's largest, treating a billion gallons of wastewater per day, uses the waste for land reclamation. In the past 20 years, the system has been studied for meat packing wastes, and there are several plants operating commercially. It has also been studied for cotton kiering liquor, brewery wastes and alcohol distillery wastes.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy demands are relatively low; some electric power is needed to mix the reactor contents, recycle some of the effluent sludge to the reactor and heat the incoming sludge. Essentially all of the power for the heat exchanger is provided through production of methane gas.

The presence of arsenate or mercury in anaerobic digestors could lead to formation of toxic compounds.

In municipal wastewater treatment plants, costs for anaerobic digestion are difficult to segregate. Estimates for a facility treating 100,000 gal/day of sludge with 5% solids would be: capital investment, $1.25 million, annual fixed costs would be $219,000, and variable costs $171,000. The cost for treating 10^3 gallons would be $10.69.

V. OUTLOOK FOR WASTES

There seems to be a potential for disposal of feed lot wastes, culture material from pharmaceutical processing, and food processing wastes. For industrial processing sludges, the method may be suitable if there is a steady volume and flow, oil and grease are removed, and soluble metal content is low.

BIOLOGICAL TREATMENT: COMPOSTING

I. CONCLUSIONS AND RECOMMENDATIONS

Composting provides a means of achieving aerobic digestion of organic wastes by microorganisms in the presence of their own released heat. It is the only biological treatment process relatively insensitive to toxicants and it encourages adsorption of metals. Costs are higher than for other biological processes, but lower than for incineration.

II. PROCESS

Composting basically involves piling ground waste in windrows and aerating the piles by periodic turning. All that need be done is scheduling of spreading and turning with earthmoving equipment, adding some nutrients and alkalis if necessary, and providing for collection of leachate and runoff water to protect groundwater. There are over 30 process modifications involving rotating drums, forced aeration, etc. Complete digestion of most organic wastes take place in three or four months, although refinery wastes or other difficult organics may take up to a year.

III. APPLICATIONS TO DATE

Systematic composting has been widely used in Europe, where there is a ready market for composted waste as an organic soil conditioner. Most of the demonstration projects in the United States have closed for lack of a market for humus, but some cities use this cost-effective disposal technique for municipal refuse and give the compost away. Chicago uses the system to dispose of high-strength organic sludges, and several petroleum refineries use it for refinery wastes. It has also been used for cannery solids, pharmaceutical and meat packing sludges.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy demand is low, limited primarily to fuel costs to operate earthmoving equipment and pumps.

The only emissions from composting are carbon dioxide, steam, a liquid effluent containing partially oxidized organics and a barnyard smell indicative of healthy microbial activity.

Costs for composting are about $30/thousand gallons of influent, exclusive of land acquisition or further treatment of collected leachate. The capital expenditure to handle 100,000 gpd would be $1.5 million; fixed costs $275,000 annually and variable costs $802,500.

V. OUTLOOK FOR WASTES

Composting is applicable to high-organic wastes, including oils and tars and industrial processing sludges.

BIOLOGICAL TREATMENT: ENZYME TREATMENT

I. CONCLUSIONS AND RECOMMENDATIONS

Enzyme treatment of industrial processing wastes is totally impractical. Enzymes catalyze specific reactions and cannot adapt well to the varying composition of typical waste streams. Furthermore, enzyme production is very expensive.

II. PROCESS DESCRIPTION

Enzymes are highly selective chemical catalysts which act on specific molecules. The urease enzyme, for example, breaks down urea into carbon dioxide and ammonia. A hydrolase enzyme derived from yeast has been shown to oxidize phenol to carbon dioxide and water. The cellulose enzyme, produced by a stream of fungus, *Trichoderma viridi*, catalyzes the hydrolysis of cellulose to glucose.

III. APPLICATIONS TO DATE

There are no known full-scale applications of enzyme treatment processes in hazardous waste management. There are commercial applications in meat tenderizing, de-hairing of hides prior to tanning, cheese-making, pharmaceutical manufacture, and detergent production.

The Army's Natick Research and Development Command is operating a 1000 lb/mo. pilot plant to convert waste paper into glucose. A number of Government, university, and industrial laboratories are investigating the use of lactose for recovery of monosaccharides from cheese whey. Groups at Oak Ridge National Laboratories and the University of Pennsylvania have studied the enzyme decomposition of phenol.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Due to the specificity of enzyme reactions and the fact that current waste treatment applications are limited in number and lab scale, no useful generalizations can be made about energy, economics, or potential environmental impacts.

V. OUTLOOK FOR WASTES

Enzyme treatment may be useful for specialized industrial applications, particularly in cases where salable reaction products result. Enzymes have little or no potential in general waste treatment.

BIOLOGICAL TREATMENT: TRICKLING FILTERS

I. CONCLUSIONS AND RECOMMENDATIONS

The trickling filter process is a proven technology for the decomposition of organics in waste streams with less than 1% suspended solids. The process brings the wastewater in contact with aerobic microorganisms by trickling the water over media supporting the microorganisms. BOD removal efficiencies range from 50 to 85%. The process is used in industry to accept wastewater loading variations and provide a relatively uniform effluent for treatment by other biological processes, such as activated sludge.

II. PROCESS

Wastes are sprayed through the air to absorb oxygen, and then allowed to trickle through a bed of rock or synthetic media coated with a slime of microbial growth. Process modifications employ various media and depths to retain the microorganisms under varying hydraulic and effluent recycle conditions. The primarily metabolic processes are aerobic, and the microbial population is similar to the activated sludge population. However, because of the relatively short contact time, the percentage removal of organics is not as great.

The process involves open tanks or towers to house the filter packing, followed by effluent clarifiers. Recycle pumps may be used to recirculate filter effluent. A rotating spray dosing system feeds influent wastewater to the filter surface.

III. APPLICATIONS TO DATE

Trickling filters have been extensively used in sewage treatment and in treatment of refinery wastewaters containing oil, phenol, and sulfide. They are applicable to the same industrial waste streams as the activated sludge process, including cannery, pharmaceutical, and petrochemical wastes.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy demands are low, as little as one-tenth that of activated sludge treatment. Dilute wastewater is treated at a total cost between 10 to 30¢ per 1000 gallons; for concentrated waste requiring filter recycle the cost may be $2 per 1000 gallons. The process effluents are a liquid wastewater from which a major portion of the dissolved organics have been removed and a biomass sludge.

V. OUTLOOK FOR WASTES

The process could be used in sequence with other biological treatment, such as activated sludge, but it is not generally efficient enough to use as the sole method of biodegradation.

BIOLOGICAL TREATMENT: WASTE STABILIZATION PONDS

I. CONCLUSIONS AND RECOMMENDATIONS

Waste stabilization ponds utilize natural biodegradation reactions in wastewaters containing less than 0.1% solids with low concentrations of organics. The process is more sensitive to concentrations of inorganics and suspended solids than any of the other biological treatments discussed in this report. It is suitable for industrial wastes only where preliminary treatment has removed most contaminants and final effluent polishing is needed before discharge to a receiving water.

II. PROCESS

Waste stabilization ponds are large shallow basins where wind action provides aeration and a mixed autotrophic and heterotrophic microbial population provides decomposition of organics over a long retention time. Deep ponds, more than 4 feet deep, may promote anaerobic decomposition of settled sludge.

III. APPLICATIONS TO DATE

Waste stabilization ponds have been widely used for sanitary sewage and dilute industrial wastes, mostly to provide final effluent polishing. Industries using the method include meat and poultry packing, canneries, dairies, iron and steel works, paper and pulp mills, textile mills, oil refineries and petrochemical plants.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Large land acreage is the principal capital cost; energy and chemical requirements are insignificant. Total costs for treating dilute wastewaters in unlined basins range from 5 to 15¢ per 1000 gallons; for more concentrated waste streams in clay-lined basins, the cost is about $1.70 per 1000 gallons. Energy is needed only for pumping. A polished liquid effluent and some biomass sludge are the end-products.

V. OUTLOOK FOR WASTES

The process can be employed only where substantial land acreage is available and where climate is suitable. Toxic inorganics must be removed before waste stabilization ponding because of the system's high sensitivity to inhibitors. The use of the method for final polishing provides extra insurance that final effluent guideline limitations will be met.

CALCINATION

I. CONCLUSIONS AND RECOMMENDATIONS

Calcination is a well established process, and one of the few that can satisfactorily handle sludges. Calcination is recommended as a one-step process for treatment of complex wastes containing organic and/or inorganic components. The organics are destroyed; the inorganics are generally reduced in volume and converted into a form of low leachability suitable for landfill.

II. PROCESS DESCRIPTION

Calcination is a thermal decomposition process, generally operated around 1000°C at atmospheric pressure. It can be applied to aqueous solutions, slurries, sludges, and tars to drive off volatiles and to produce a dry powder or sintered solid. Typical calciners include the open hearth, rotary kiln, and fluidized bed.

III. APPLICATIONS TO DATE

Industrial applications include production of cement, lime, magnesia, titania, and wall plaster, and smelting of sulfide and carbonate ores. Waste treatment applications include recalcination of lime sludges from water treatment plants; coking of heavy residues and tars from petroleum refining operations; concentration and volume reduction of liquid radioactive wastes; and treatment of mixed refinery sludges containing hydrocarbons, phosphates, and compounds of Ca, Mg, K, Na, S, Fe, and Al.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements are generally high, but depend on the water and organic content of the waste stream. Calcination of dry material requires about $1\text{-}3 \times 10^6$ Btu/ton of solid product; calcination of a sludge or slurry with 90% water requires about 20×10^6 Btu/ton of solid product. If this waste stream contains a combustible organic fraction, the energy requirements are reduced.

In general, calcination systems will require fairly extensive air pollution control equipment, including particulate-removal devices, wet scrubbers, and possibly final gas adsorption systems.

Capital investment costs for a calciner are in the range of $10,000-$30,000/ton of throughput daily. Operating costs are highly variable, depending on the water and organic content of the waste stream, and the possibilities for resource recovery credits.

V. OUTLOOK FOR WASTES

Calcination has been used widely in industrial and waste treatment applications. Its use is likely to expand, particularly in the treatment of tars, sludges, and other residues which present particularly difficult problems for disposal.

CATALYSIS

I. CONCLUSIONS AND RECOMMENDATIONS

Whenever a waste stream can usefully be treated by a chemical transformation process, the possibility of catalyzing the reaction should be considered. In general, if a transformation can be successfully catalyzed, operating costs and energy requirements will be reduced.

II. PROCESS DESCRIPTION

Catalysis is not a process in itself, but rather a modification of the rate or mechanism of chemical reaction processes through the use of catalysts, which are themselves unchanged at the end of a reaction.

III. APPLICATIONS TO DATE

The industrial applications of catalysts in the petroleum refining, chemical, pharmaceutical, and textile industries are legion.

In the field of waste treatment, catalytic oxidation is used quite widely as an alternative to incineration in the decomposition of waste organics. A number of catalytic processes have been investigated in the laboratory for destruction or detoxification of chlorinated pesticides, oxidation of cyanides, sulfides, and phenols, decomposition of sodium hypochlorite solutions, and conversion of mixed carboxylic acid waste streams to fumaric acids for recovery.

IV. ENERGY, ENVIRONMENT, ECONOMICS

In general, a catalytic process operates at a much lower temperature than the equivalent non-catalytic process and hence consumes less energy.

Environmental impacts are generally the same as those of the non-catalytic process.

Catalytic processes may be higher in capital costs than non-catalytic processes in some cases. However, the less severe operating conditions (lower temperatures and/or pressures) almost always result in lower overall operating costs.

V. OUTLOOK FOR WASTES

As the use of chemical processing in waste treatment increases, the effort to develop catalytic processes should be increased as well. A great deal of work is needed to demonstrate the commercial practicality of catalytic reactions tested in the laboratory, and exploratory work could be useful on catalytic hydrogenation and low-temperature air oxidation.

CENTRIFUGATION

I. CONCLUSIONS AND RECOMMENDATIONS

Centrifugation is a well-developed liquid/solid separation process being used in a variety of full-scale applications for material processing and waste treatment. In treating hazardous wastes, centrifugation can be used to greatest advantage to increase the solids concentration, and thereby reduce the volume, of a high concentration liquid/solid mixture (sludge) by partially separating the liquid and solid phases ("sludge dewatering").

Centrifugation is generally technically and economically competitive with other sludge dewatering processes (e.g., vacuum filtration or the use of filter presses) and should be considered as a potential process for concentrating hazardous waste sludges and slurries. Equipment is commercially available in a large variety of sizes and configurations.

II. PROCESS

Centrifugation is a physical process whereby the components of a fluid mixture are separated mechanically by the application of centrifugal force, applied by rapidly rotating the mass of fluid within the confines of a rigid vessel. Centrifugal forces acting on the revolving mass of fluid cause the solids suspended in the fluid to migrate to the periphery of the vessel where they can be separated. The particles are removed as a liquid/solid mixture significantly more concentrated than the original liquid.

III. APPLICATIONS TO DATE

Some common applications of centrifugation are in separating oil and water mixtures; clarification of viscous gums and resins; classification and removal of oversize particles and unground pigment from lacquers, enamel and dye paste; clarification of essential oils, extracts, and food products, such as homogenized milk and fruit juices; separation of micro-organisms from fermentation broths, recovery of finely divided metal such as silver from film scrap and platinum from spent catalyst; separation of acid sludges from the acid treatment of petroleum; recovery of crystalline solids from brine; dewatering of fibrous solids such as paper pulp and chemical fibers; dewatering and removal of starch from potato fibers, etc. Probably the main application for centrifuges at present is the dewatering of waste sludges.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Power requirements for centrifugation are typically 0.3-1.2 horsepower per gallon per minute of inlet waste feed. Power consumption is equal to or slightly greater than for other sludge dewatering processes.

For most sludge dewatering purposes, centrifugation is generally cost-competitive with other dewatering processes such as vacuum filtration or press filtration.

A conveyor bowl type centrifugation system capable of dewatering 6 tons per day of sludge (dry basis) will have an installed capital cost of approximately $140,000 and a total operating cost (including amortization) of $34.50 per ton of solids dewatered. In most applications, costs range from $20-$45/ton.

V. OUTLOOK FOR WASTES

The major application of centrifugation to waste treatment is the dewatering of waste sludges generated by water pollution control systems. Centrifuges have for many years been used on biological sludges from municipal treatment plants and from pulp and paper mills. Some expect the technique to replace vacuum filtration as the most common dewatering technique, especially for sticky or gelatinous sludges. It will also find further application in removing soluble metals from wastewater, as from the wet scrubbers used in the steel industry, to dewater sludges generated from sulfur dioxide air pollution control systems, etc.

Because it is capable of totally closed operation, centrifugation is particularly well suited to treating liquids that are volatile, flammable, or otherwise pose health and/or safety hazards to operating personnel.

CHLORINOLYSIS

I. CONCLUSIONS AND RECOMMENDATIONS

Chlorinolysis is capable of converting most liquid chlorinated hydrocarbons completely to carbon tetrachloride. It is not really a waste treatment process, but a manufacturing process that uses chlorocarbon waste streams and residuals as feedstocks. The process has excellent resource recovery potential (sufficient wastes are generated in the Gulf Coast region to support at least one 25,000 ton/yr chlorinolysis plant) if there is a market for the carbon tetrachloride. There may be, however, legal and institutional problems that might hinder transfer of wastes from generators to an operating chlorinolysis unit.

II. PROCESS

At temperatures around 500°C and pressures of about 200 atm in the presence of excess chlorine, the carbon-carbon bonds of hydrocarbons can be broken, and the molecules recombined to react with chlorine to form carbon tetrachloride. Because liquid chlorine is highly reactive, reactors and piping must be high-purity nickel, surrounded by a stainless steel jacket. The organic feedstock and preheated chlorine are introduced to the reactor, which is heated to initiate chlorinolysis; subsequently the process provides its own heat. At the end of the process, the pressure is released and the products are cooled and drawn off. Subsequent processing by distillation yields carbon tetrachloride, the principal product for sale.

III. APPLICATIONS TO DATE

This is not a waste treatment process, but a production process that can utilize waste streams. A semicommercial plant to produce 6000-8000 tons/year has been operating in Germany and a 50,000 ton/year plant is planned for the same site.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Electricity and fuel requirements per ton of carbon tetrachloride are relatively small – 135 kWh and 794 Btu, respectively. Chlorinolysis offers the opportunity of resource recovery, but the process involves hydrochloric acid and phosgene gas effluents. Neutralization of the effluent streams will produce sodium hypochlorite, which is toxic to aquatic life.

Capital and operating costs for a plant processing 25,000 metric tons/year of mixed chlorinated hydrocarbon wastes are estimated at $19,700,000/year; the process could produce carbon tetrachloride at 10.2¢ per lb, and the selling price is now 19¢.

V. OUTLOOK FOR WASTES

Chlorinolysis is an efficient, cost-effective process for recovering carbon tetrachloride from chlorinated hydrocarbon waste streams. The outlook for the process depends on the future demand for carbon tetrachloride, and the availability of a continuing supply of suitable wastes.

DIALYSIS

I. CONCLUSIONS AND RECOMMENDATIONS

Dialysis is one of the earliest membrane processes. It can separate salts and low molecular weight organics from colloids and high molecular weight solutes in aqueous waste streams. However, both of the output streams are more dilute than the feed stream, and neither is likely to be more suitable for disposal or recovery than the feed stream. Hence, dialysis has little or no potential for general waste treatment applications.

II. PROCESS DESCRIPTION

A solute-containing feed stream is passed across one free of a semi-permeable membrane and a higher volume wash stream is passed across the opposite face. Small solute molecules are transferred to the wash stream by diffusion across the membrane. Larger molecules and colloids are retained in the feed stream.

III. APPLICATIONS TO DATE

The best known current application of dialysis is hemodialysis, which removes salts, urea, and other wastes from the blood of people suffering from chronic kidney failure. Since the 1920's, dialysis has been used in the rayon industry to separate caustic soda from hemicellulose wastes. There are also other smaller scale applications in pharmaceutical and biochemical laboratories for special production and purification. Dialysis equipment is available commercially.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements are low, being limited to the pumping of feed and wash streams.

The two diluted product streams could prevent difficult disposal problems if not reusable.

Capital costs depend more on the amount of material to be separated than on the waste stream throughput. A commercial dialyzer separating 1000 lb/day of solute would cost about $3000.

V. OUTLOOK FOR WASTES

Dialysis is a mature technology; no major new developments are expected which would make the process at all useful for hazardous waste treatment.

DISSOLUTION

I. CONCLUSIONS AND RECOMMENDATIONS

Dissolution is a first step that removes major or minor constituents from solids. The process is applicable to any solids that can be wetted by a suitable liquid. We recommend that more emphasis be placed on more complete characterization of solids to aid in specification and testing of possible dissolution processes. Efforts should also be made to utilize lower quality or waste reagents where possible.

II. PROCESS

Dissolution may be defined as the complete or partial transfer of one or more components from a solid to a liquid phase in contact with the solid. The reaction involves some degree of chemical transformation, such as solvation, ionization, or oxidation. The solids are contacted by the reagent in a mixer, following which the slurry is separated. Heat may be applied to speed the process and provide increased solubility. Solids can be treated sequentially with different reagents to remove components selectively. The products are a wastewater stream that requires further treatment, and residual solids that may be suitable for disposal, reuse, or further treatment.

III. APPLICATIONS TO DATE

Dissolution has been widely used in metallurgy since the early 1800's and in the synthetic chemical industry since its beginning. Many of these applications (e.g., separation of metals from ores) are closely related to treatment of inorganic wastes, but there appears to be little large-scale application to waste treatment. One installation involves production of chemicals for agriculture and other use from galvanizing wastes and flue dust. Another is used for recovery of metallic copper from scrap, and a semi-commercial plant is being considered for recovery of metal from plating slimes. Several pilot and laboratories studies are now going on.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements are limited to electricity for mixing and pumping, and heat, if required. Emissions to water are not harmful if the liquors used and produced are conveyed to the next process step without inadvertent losses. No land disposal problems are anticipated if leached solids are adequately washed to remove leach liquor. Emissions to air will be significant only when gas is evolved in the process, or where an unintended reaction takes place (e.g., reaction of traces of sulfides in water to give off hydrogen sulfide).

The diversity of materials potentially suitable for dissolution and the circumstances of reaction vary considerably. The process is especially sensitive to chemical and labor costs.

An approximate cost for dissolving a hypothetical metal finishing sludge waste using fresh sulfuric acid reagent would be: $61 per ton of input solids or $300 per ton of desired metal removed; the cost of sulfuric acid is $24 per input ton.

V. OUTLOOK FOR WASTES

Further applications for waste treatment depend on cost-sensitive factors, such as utilization of waste reagents, and on better understanding of composition of sludges and mixed metal compounds.

DISTILLATION

I. CONCLUSIONS AND RECOMMENDATIONS

Distillation is a unit operational process that is fully developed commercially and is often employed to separate or purify liquid organic product streams. It is a non-destructive process, and practical limitations are primarily economic. With more stringent limitations on air, liquid effluents, and land site disposal, and with the rising cost of organic chemicals, distillation could become more competitive with other methods for recovery of useful materials from waste streams.

II. PROCESS

The basic principle of distillation is as simple as it is old: when a mixture of liquids is boiled, the vapor usually differs in composition from the liquid that remains. Only since the 19th century, however, has distillation been conducted on a large scale as a steady-state operation.

In general, a feedstock is charged to a large vessel (still) which is heated, and vapors are removed as they are formed, and then condensed. There are a number of variations on this basic process.

III. APPLICATIONS TO DATE

Distillation has wide industrial application in petroleum fractionation, organic chemical purification, organic chemical intermediate manufacture, solvent recovery, and cryogenic air separation to produce oxygen, nitrogen, and argon.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Because of the variables involved, there is no such thing as a typical cost on a unit product or unit feed basis.

Distillation creates no air or liquid effluent problems.

An economic analysis of a system that might be used for different types of organic liquid waste streams was made, based on a capacity of 8000 lb 20% acetone in water waste/day. The solvent recovery cost in this system would be 4.2¢/lb acetone.

V. OUTLOOK FOR WASTES

Hazardous wastes that can be economically treated by distillation (for organic chemical or solvent recovery) include liquid organic mixtures, such as solvent mixtures recovered from carbon air adsorption units, paint wastes, organic-containing plating wastes, and lube oil. The process is not suitable for treatment of thick, polymeric materials, slurries, sludges, or tars that can cause operational problems. The types and quantities of organic solvent and chemical wastes that are treated by distillation will increase as effluent regulations become more stringent.

ELECTRODIALYSIS

I. CONCLUSIONS AND RECOMMENDATIONS

Electrodialysis has not been employed on a full-scale basis for any hazardous waste problem, per se. Nevertheless, it may have applicability where it can be tied into further concentration or reuse schemes. It will profit by the fact that it is a mature technology with well-known performance characteristics and price, and therefore can be easily evaluated as a potential component of any multi-process treatment being considered.

II. PROCESS

The general principle of electrodialysis is the separation of an aqueous stream under the action of an electric field into two streams, one enriched and one depleted. Success depends on synthetic membranes, usually based on ion-exchange resins, which are permeable only to a single-charge type of ion. Cation exchange membranes permit passage of only positive ions, while anion membranes permit only negatively charged ions to pass through.

The feed water passes through compartments formed by the spaces between alternating cation-permeable and anion-permeable membranes held in a stack. At each end of the stack is an electrode having the same area as the membranes. A d-c potential applied across the stack causes the positive and negative ions to migrate in opposite directions. Feed material is first filtered to remove suspended particles that could clog the system. An operating plant usually contains many recirculation, feedback and control loops and pumps to optimize the concentrations and pH at different points for most efficient operation.

III. APPLICATIONS TO DATE

Electrodialysis has been used for desalination since the 1950's. The largest number of installations is in the production of potable water from brackish well or river water. Hundreds of such units, some of which can handle more than one million gallons per day, are in use throughout the world.

In the food industry, electrodialysis is used for desalting whey and de-ashing sugar. The chemical industry uses the technique for enriching or depleting solutions, and for removing mineral constituents from product streams.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Electrical requirements vary, but conventional systems take about 5 kWh of energy for each 1000-ppm reduction of salt in each 1000 gal. purified product water and up to 3 kWh to pump each 1000 gal. products.

The product streams must be recycled, sold, or otherwise disposed of. Electrodialysis may generate low levels of toxic or flammable gases that might present a hazard in an enclosed space.

The capital costs for electrodialysis are modest, about 20-25% of the total cost of water treatment. Both capital and direct operating costs are dependent on the volume of water treated and on the salts removed. Total water production costs of less than \$.50/10^3 gal are reported for salt reduction from 2000 ppm to 500 ppm in plants treating 10^6 gal/day or more. Other plants may have higher costs or may receive significant credits for reclaimed material.

A typical electrodialysis system to treat rinse tanks from an acid nickel plating line might cost about \$6.00/10^3 gal.

V. OUTLOOK FOR WASTES

Pilot operations have been carried out in the desalting of sewage plant effluent, sulfite-liquor recovery, and acid mine drainage treatment. Treatment of plating wastes and rinses, particularly to salvage chromium, may have some potential.

ELECTROLYSIS

I. CONCLUSIONS AND RECOMMENDATIONS

Electrolytic processes may be considered for reclaiming heavy metals, including toxic metals from concentrated aqueous solution and for polishing dilute metallic wastewaters. They are not generally useful for dissolved organics, organic waste streams or viscous and tarry liquids.

II. PROCESS

Electrolysis refers to the reactions of oxidation or reduction that take place at the surface of conductive electrodes immersed in an electrolyte, under the influence of an applied potential.

III. APPLICATIONS TO DATE

Electrolysis, including electroplating and anodizing, has been an important process of industrial chemistry for many years. Chlorine production, for example, depends on electrolysis, and many commercial metals are refined by electrolytic processes. Metals may be obtained from primary ores, and magnesium and aluminum are processed by electrolysis in molten salt baths. Electrolysis for waste treatment has been employed to a limited extent depending largely on costs. The most frequent application is the partial removal of concentrated metals such as copper from waste streams for recycle or reuse. Other applications which have been successfully piloted include oxidation of cyanide wastes and separation of oil-water mixtures.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Electrical energy costs range from 10 to 35% of total operating costs, with treatment of concentrated metals at the low end, and dilute streams or cyanide treatment at the high end.

Gaseous emissions may exist; some may be vented to the atmosphere, others may have to be scrubbed or otherwise treated. The process wastewater may be reusable or disposable, or may have to undergo further processing.

Costs are highly dependent on the concentration and nature of the undesirable material. Electrolysis may offer significant trade-offs between capital and operating costs, depending on chemical and economic variables.

ELECTROPHORESIS

I. CONCLUSIONS AND RECOMMENDATIONS

No suitable equipment for electrophoretic treatment of hazardous wastes is available. Many critical problems would have to be solved before such equipment could be developed, and even if the design problems were solved, there is no assurance that the process would be operationally practical. Further consideration of electrophoresis cannot therefore be justified.

II. PROCESS DESCRIPTION

Electrophoresis is the transport of electrically charged particles under the influence of a DC electric field. The charged particles (generally colloids in the 1-20μ size range) migrate to a collecting membrane for subsequent removal.

III. APPLICATIONS TO DATE

Electrophoresis is used extensively as a laboratory tool in the analysis and separation of proteins, polysaccharides, and nucleic acids. It has also been used commercially for creaming of rubber latex, and for fractionation of animal sera for veterinary vaccines. Numerous proposed applications have been researched and shown to be technically feasible. These include deposition of paints, polymers, ceramics, and metals. The process has also been considered for water purification (e.g., for separation of emulsions, and for color, virus, and algae removal).

IV. ENERGY, ENVIRONMENT, ECONOMICS

In aqueous systems, the electrical energy requirements are of the order of 7 kWh/ 1000 gal.

The process may evolve gases from electrode reactions. Both the concentrated sludge and the "treated" liquid may require subsequent disposal.

Capital costs would be lower than the costs for electrodialysis. Operating costs might be in the range of $0.50-2.00/1000 gal, depending on the application.

V. OUTLOOK FOR WASTES

At least 5-10 years of effort would be required to develop electrophoresis equipment for waste treatment. In view of the lack of scientific and practical guides available, and the very significant problems of controlling electrode reactions, pH, conductivity, flow, temperatures, and membrane plugging, there is even some question whether an R&D effort would be successful.

EVAPORATION

I. CONCLUSIONS AND RECOMMENDATIONS

Evaporation is a well-defined well-established process, used throughout industry. It is capable of handling liquids, slurries, sludges, both organic and inorganic, containing suspended or dissolved solids or dissolved liquids where one of the components is nonvolatile. It is energy-intensive, and specialized equipment can be expensive.

II. PROCESS

The process and equipment for applying heat to the solution are similar to that for distillation, except that the vapor is not separated. Open, direct-fired pans or solar evaporation from ponds are still used in some applications, but most evaporators are heated by steam condensing on metal tubes, through which the solution flows. Usually the steam is at low pressure and the boiling liquid is under a moderate vacuum. There are numerous variations on equipment and processes, depending on the application.

III. APPLICATIONS TO DATE

In the chlor-alkali industry, evaporation is used to concentrate caustic soda and to produce calcium chloride. Evaporation of saline water to provide fresh water is well established; U.S. plants have a capacity of about 67 million gpd. Concentration of sulfuric and hydrochloric acids, citrus fruit juice, phosphates, and milk whey; crystallization of salts, sugar; dehydration of Glaubers salt, sulfur sludges are all well established.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements vary considerably within a range of 100 to 1100 Btu/lb liquid evaporated, with the average closer to the lower figure.

There are generally no pollution problems with evaporation vapors. Where the vapors contain organics, the liquid is condensed and either disposed of or recovered by another process, such as distillation.

Economic analysis of an operation to concentrate 100,000 gallons per hour of kraft black liquor shows capital investment of $1.3 million. Yearly operating costs would be $1.06 per 1000 lbs of water.

V. OUTLOOK FOR WASTES

Evaporation is already used in the treatment of radioactive wastes, and is very effective where suspended solids content is high and other methods are difficult. A combination of evaporation and simultaneous combustion is used to dispose of TNT wastes. Other applications include photographic chemicals, papermill wastes, molasses distillery wastes, and pickling liquors. Evaporation is not suitable for tars, solids, dry powders, or gases.

FILTRATION

I. CONCLUSIONS AND RECOMMENDATIONS

Filtration is a well-developed liquid/solid separation process currently applied to the full-scale treatment of many industrial wastewaters and waste sludges. For the treatment of hazardous wastes, filtration can be used to perform two distinctly different functions:

1) Removal of suspended solids from a liquid (usually aqueous) waste stream with the objective of producing a purified liquid.

2) Increasing the solids concentration, and thereby reducing the volume, of a high concentration liquid/solid mixture (sludge) by removing liquid from the mixture ("sludge dewatering").

As a wastewater treatment process, filtration is usually most applicable when following some form of flocculation and/or sedimentation. As a sludge dewatering process filtration is usually technically and economically competitive with other dewatering processes.

We recommend that filtration be considered as a potentially applicable process for hazardous waste treatment applications requiring the separation of liquid and solid phases.

II. PROCESS

Filtration is a physical process whereby particles suspended in a fluid are separated by forcing the fluid through a porous medium. As the fluid passes through the medium, the suspended particles are trapped on the surface of the medium and/or within the body of the medium. Filter media can be a thick barrier of a granular material, such as sand, coke, coal, or porous ceramic; a thin barrier, such as a filter cloth or screen; a thick barrier composed of a disposable material such as powdered diatomaceous earth or waste ash. The pressure differential to move the fluid through the medium can be induced by gravity, positive pressure, or vacuum. The intended application has a great influence on both the type of filter and its physical features.

III. APPLICATIONS TO DATE

The inorganic chemicals industry employs various forms of filtration to separate precipitated product from waste material. They are commonly used in the manufacture of titanium dioxide, sodium dichromate, aluminum sulfate, and magnesium. The organic chemicals industry also employs filter techniques, e.g., removal of acetylene carbon particles from aqueous quench streams, and removal of dye particles from the reaction bath. Rotary vacuum filters are used to remove impurities in the processing of sugar. Vacuum filtration is often used to remove impurities from lube oils. Boiler feed water and many types of industrial process water have stringent specifications on suspended solids. Filtration is often used in conjunction with precipitation, flocculation, and sedimentation to remove these solids. Filtration is also used as the final step in many industrial wastewater treatment plants.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements for filtration are relatively low. A vacuum filtration system capable of dewatering 36,000 gal/day of sludge containing 6 tons of solids will have a power requirement of only 25 horsepower.

The cost of treatment for both vacuum filtration and press filtration is usually within the range of $20-$45/ton of solids treated (dry basis). For liquid purification the cost of filtration by granular media filters usually varies from $0.10-$0.50 per 1000 gallons of wastewater treated.

V. OUTLOOK FOR WASTES

Major applications are and will be in the removal of suspended solids from wastewater streams and in the volume reduction (dewatering) of waste sludges and slurries. As more and tighter restrictions are placed on wastewater discharge, filtration will often be used after precipitation, flocculation, and sedimentation.

Decreased availability of solid waste disposal sites will further encourage the dewatering of sludges prior to disposal.

Non-aqueous liquids can be subjected to filtration for removal of suspended solids, but highly viscous semi-liquids such as tars are generally not amenable to filtration.

FLOCCULATION, PRECIPITATION, AND SEDIMENTATION

I. CONCLUSIONS AND RECOMMENDATIONS

Flocculation, precipitation, and sedimentation are fully-developed processes currently used in a wide variety of industrial processing and waste treatment applications. While flocculation, precipitation, and sedimentation are individual process steps, they are interrelated, and are often combined into a single overall treatment process. They can be quite readily applied to a variety of aqueous hazardous wastes for the removal of precipitable substances, such as soluble heavy metals and for the removal of solid particles suspended in the liquid. We recommend that these processes be given serious consideration for removal of heavy metals and/or suspended solids from an aqueous waste stream. Although the process theoretically can be used to treat non-aqueous liquids, such applications are very rare. Precipitation, flocculation, and sedimentation are generally unsuitable for treating heavy slurries, sludges, and tars.

II. PROCESS

Flocculation is the process whereby small, unsettleable particles suspended in a liquid are made to agglomerate into larger more settleable particles. Precipitation is a physicochemical process where some or all of a substance in solution is removed from the solution and transformed into a second (usually solid) phase. Sedimentation is a purely physical process whereby particles suspended in a liquid are made to settle by means of gravitational and inertial forces acting on both the particles suspended in the liquid and the liquid itself.

III. APPLICATIONS TO DATE

The processes have long been widely used for a variety of industrial applications, such as in the manufacture of many organic chemicals, the preparation of metal ores, and the preparation of sugar.

Practically every industry that discharges a process wastewater stream contaminated with suspended and/or precipitable pollutants employs some form of precipitation, flocculation and/or sedimentation. Examples are: removal of heavy metals from iron and steel industry wastewater; removal of fluoride from aluminum production wastewater; removal of heavy metals, from wastewaters from copper smelting and refining, and from the metal finishing industry.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy consumption is very low compared to other processes. The processes produce a waste sludge, which can often present a serious disposal problem.

A large (over 5 million gallons per day) system employing only sedimentation with no flocculating chemicals will typically treat wastewater at a cost of $0.10-$0.50 per 1000 gallons treated.

A moderate size (0.5-5 million gallons per day) system employing precipitation, flocculation, and sedimentation and using moderate dosages of precipitating/flocculating agents will usually treat wastewater at a cost of $0.50-$3.00 per 1000 gallons.

Small, especially designed systems (less than 0.5 million gallons per day) using high dosages of precipitating/flocculating agents can have costs that are higher, but these will rarely exceed $6.00 per 1000 gallons.

V. OUTLOOK FOR WASTES

Precipitation, flocculation, and sedimentation are generally practical, effective, and relatively low-cost processes for the removal of precipitable soluble substances and suspended particles from aqueous waste streams. The processes are particularly suitable for the treatment of high volume/low concentration waste streams.

In determining the applicability of precipitation, flocculation, and sedimentation to specific waste streams, true research and development is usually unnecessary. Past experience and simple laboratory treatability tests are usually all that is necessary in determining applicability.

FLOTATION

I. CONCLUSIONS AND RECOMMENDATIONS

Flotation is a physical-chemical method of separating solid particles suspended in a liquid, when the valuable products to be separated constitute less than 10% of the total solids. Although flotation has found only limited application outside the mineral industry, it is our belief that, with further research and development, the technique could be used to separate many types of components from mixtures of solids.

II. PROCESS DESCRIPTION

The material is crushed or ground, mixed with water and reagents into a slurry or pulp, and agitated. Air bubbles carry the selected materials to the surface to form a stabilized froth, which is then skimmed off, while the waste materials remain. By using the correct reagents, it is possible to separate similar materials from each other. Some installations separate only one valuable component from waste; others separate two, three, or even four products.

III. APPLICATIONS TO DATE

Although flotation has been applied principally to mineral processing to separate valuable ore from tailings, a few other applications seem to have potential. When cellulose is recycled from paper, flotation can be used to remove ink, pigments, and coatings. A few years ago three plants in the United States treated about 25,000 tons of paper per year in this manner.

Other possible applications outside the mineral industry, though there are no commercial plants, are as a means of removing cyanide from solutions or mixed suspensions. In one test, about 95% of the cyanide could be removed. Research also shows that microorganisms can be floated, concentrated, and removed from a suspension.

IV. ENERGY, ENVIRONMENT, ECONOMICS

The typical conventional flotation plant is a relatively large consumer of energy, averaging about 15 kWh/ton milled. Only about 15% of the total is consumed in the flotation step, with most of the energy used for crushing and grinding.

Air emissions are not significant, since flotation is a wet process. Dust emissions occur at the ore crusher and at conveyor transfer points but are controlled with collecting hoods and water sprays. The waste effluent goes to a tailings dam from which water may be recycled, especially in arid areas.

Costs depend on the size and nature of the process. Operating costs for sulfide ore flotations vary from $4/ton ore processed for a 500T/day plant to $1.50/ton for a 10,000 T/day plant.

V. OUTLOOK FOR WASTES

The best application for the flotation process would be for separating a hazardous solid from one that is not. Another application would be to separate all solid materials in a slurry; however, it is difficult to see any reason for doing it this way, when the simpler process of thickening and filtration would accomplish the same purpose. Heavy metal ions (copper, nickel, cadmium) and cyanides might be amenable to removal by this process, as well as such inorganics as carbonyls and fluorides. As far as we know, however, no work has been done to utilize the process.

On the other hand, some of the reagents commonly used for mineral and ore processing are themselves hazardous and, if used carelessly, may appear in the tailings. Care must be exercised in their use and control.

FREEZE-CRYSTALLIZATION

I. CONCLUSIONS AND RECOMMENDATIONS

Freeze-crystallization has been successfully tested for desalination of brackish waters in pilot plants. It has been demonstrated in the laboratory for hazardous waste treatment, and is expected to find commercial applications in the near future.

II. PROCESS DESCRIPTION

Freeze-crystallization involves formation of "pure" ice crystals from a solution, and concentration of dissolved solutes in a residual brine. The ice crystals may be separated mechanically from the brine, washed, and melted to yield fresh water (or solvent). The brine must be treated further, or otherwise disposed of.

III. APPLICATIONS TO DATE

A number of freeze-crystallization processes were developed for desalination, but none have become commercial. Waste treatment applications tested in the laboratory include: sulfite liquors; plating liquors; paper mill bleach solutions; arsenal redwater; solutions containing acetic acid, methanol and aromatic acids; ammonium nitrate wastes; and cooling tower blowdown.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Electrical energy requirements are in the range of about 60-75 kWh/1000 gal of product water.

The major environmental problem is associated with further treatment, or disposal of the brine. Some emissions of refrigerant (e.g., butane or freon) are possible.

Capital costs are estimated to be in the range of $600,000-$800,000. Operating costs might be in the range of $6-12/1000 gal of product water.

V. OUTLOOK FOR WASTES

Freeze-crystallization appears to be a very promising process for treatment of aqueous waste streams containing 1-10% TDS. Commercial applications are certainly anticipated within the next five years. Applications to some non-aqueous waste streams could probably be developed.

FREEZE-DRYING

I. CONCLUSIONS AND RECOMMENDATIONS

Freeze-drying (lyophilization) has no apparent potential for treating hazardous industrial wastes. Although freeze-drying is used commercially for desiccating biological and sensitive materials, it does not appear adaptable to economical waste processing on a large scale. The process is slow, costly, and energy-intensive, with limited use for removing water.

II. PROCESS DESCRIPTION

Freeze-drying is a process for subliming frozen water from a material under high vacuum. Basic equipment consists of a vacuum chamber, a vacuum source, and appropriate refrigeration and heating equipment. Suitable feeds include wet solids, sludges, and slurries.

III. APPLICATIONS TO DATE

The largest current use of this process is in the preparation of freeze-dried coffee which commands a premium price in the marketplace. It is also used in the manufacture of pharmaceutical and biological preparations.

There are no known applications to waste treatment, and none is under development.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Freeze-drying is energy-intensive and costly to operate. Capital equipment costs range from $300,000-500,000. Its pollution potential is low, except for secondary effects of energy generation.

V. OUTLOOK FOR WASTES

Freeze-drying development aimed at waste treatment is unknown and will probably remain so due to the serious limitations of the process.

FREEZING, SUSPENSION

I. CONCLUSIONS AND RECOMMENDATIONS

Freezing of sludges can aid in the agglomeration of suspended particles, which then tend to separate rapidly on thawing, leaving a clean supernatant. There are no practical applications at this time.

II. PROCESS DESCRIPTION

Suspension or simple freezing (dewatering) of sludge causes the suspended solids to agglomerate and form relatively large floc particles which are more easily removed. Freezing is accomplished naturally outdoors or through use of a refrigerant. Flocculants may be used to accelerate coalescence of suspended solids during freezing. Separated solids are screened or filtered off, and the water is further treated if necessary.

III. APPLICATIONS TO DATE

No commercial suspension freezing or freeze dewatering applications exist. Freezing alum sludges typical of waste water treatment plants has been the center of interest in the laboratory. Development of freezing for other materials is not being advanced.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements for natural freezing outdoors are small. Mechanical refrigeration requires large energy expenditures. Suspension freezing is essentially a phase separation process, and both the separated solids and the supernatant liquid would generally require further treatment prior to disposal.

Reliable cost data are not available, but are expected to be relatively high.

V. OUTLOOK FOR WASTES

Unless energy considerations are proven to be acceptable and a broader usage of suspension freezing can be found, it will remain limited in application to sludge dewatering. Its value as a viable waste treatment process remains to be demonstrated on a commercial scale.

HIGH-GRADIENT MAGNETIC SEPARATION (HGMS)

I. CONCLUSIONS AND RECOMMENDATIONS

High-gradient magnetic separation (HGMS) should be considered for removal of magnetic materials, or recovery of certain high-value, nonmagnetic materials, from waste streams. The process is particularly attractive for high-volume applications. Aqueous or non-aqueous liquids, slurries, solids, and dry powders may be treated.

II. PROCESS DESCRIPTION

HGMS is a technique for separating magnet or weakly paramagnetic particles and other nonmagnetic materials (down to colloidal particle size) from slurries, sludges, and (after chemical treatment) from solutions. The feed stream is passed through a fine ferromagnetic filter which, when magnetized, collects the magnetic material. The filter is periodically cleaned, with the magnetic material then recovered by a simple wash procedure. The removal of nonmagnetic material requires the feed to be treated with a magnetic seed (e.g., magnetite).

III. APPLICATIONS TO DATE

Current applications include clay whitening (removal of a small colored magnetic fraction), and upgrading of low-grade iron ore.

Applications currently being investigated, but not yet commercial, include: beneficiation of other ores, coal desulfurization, removal of flue dusts in air streams from blast furnaces, and wastewater treatment (including municipal wastes and steel mill wastewaters).

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements may be relatively large, especially if high magnetic fields are required. Electromagnets, used to generate fields of up to 20 kOe, have power ratings of around 400 kW for the larger machines. Disposal of the filter wash solution, if the material is not recovered, and additional treatment of treated stream may also be required.

Capital costs may be as high as $800,000, if high magnetic fields are required; they may be as low as $5,000, if the material being removed is ferromagnetic. Operating costs for high-volume applications are expected to be around 10-50¢/1000 gal for removal of ferromagnetic materials, and of the order of $1-5/1000 gal for removal of weakly paramagnetic materials.

V. OUTLOOK FOR WASTES

HGMS has attractive possibilities for the removal of ferromagnetic and paramagnetic particulates from liquids or slurries (where seeding is not required). When other nonmagnetic particles are present, the magnetic material should constitute only a small fraction of the total solids; total solids, however, may be as high as 10-15% by volume of the waste stream. Economics are probably favorable only for large-volume streams. The time frame for development is of the order of 5-10 years.

HYDROLYSIS

I. CONCLUSIONS AND RECOMMENDATIONS

Hydrolysis is potentially applicable to a wide range of waste forms and compositions. There are currently very few actual waste treatment applications, but the process does appear promising for detoxification and recovery of organics. Expanded R&D activity is recommended.

II. PROCESS DESCRIPTION

Hydrolysis generally refers to double decomposition reactions with water of the type: $XY + H_2O \longrightarrow HY + XOH$. The reactions are usually carried out at elevated temperatures and pressures, often with acid, alkali, or enzyme catalysts. Suitable feed streams include aqueous or non-aqueous solutions, slurries, sludges, or tars.

III. APPLICATIONS TO DATE

The oldest application of hydrolysis is in the production of soap from heated fats in the presence of caustic (known as saponification). Hydrolysis is also used commercially for the manufacture of a variety of organics (e.g., production of phenol from chlorobenzene; production of ethylene oxide from ethylene glycol or ethylene chlorohydrin).

Waste treatment applications are not widespread. However, in the petroleum industry, the sludge from acid treatment of light oils is often hydrolyzed to recover sulfuric acid for reuse; the other product, a tarry acid oil, may be concentrated and burned as fuel. Hydrolysis has also been used for detoxification of waste streams containing carbamates, organophosphorus compounds, and other pesticides.

Hydrolytic waste treatment processes that have shown promise in the laboratory include acid hydrolysis of waste paper to sugar; conversion of organic sludge to animal feed; and decomposition of polyurethane foam to toluene diamine and a polyol.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements vary considerably with the application, but are generally high. Steam requirements for production of fatty acids approximate 120 Btu/lb of product. Production of TiO_2 from $Ti(SO_4)_2$ requires about 1500 Btu steam/lb of TiO_2 produced.

The products of hydrolysis of a complex waste stream are not readily predictable and may be toxic.

The capital investment and operating costs are highly dependent on the specific process details. Capital investment figures for different processes range from about $2500-20,000/ton of material handled daily. Operating costs might range from 0.3-1.5¢/lb.

V. OUTLOOK FOR WASTES

Although not in widespread use as a waste treatment process, hydrolysis presents no fundamental problem. Handling of strong acids and alkalies requires care, and performing reactions at high temperatures and pressures necessitates close control and monitoring.

For hazardous wastes, hydrolysis can be adapted to handle liquids, gases, or solids. It does not appear promising for inorganic materials, but is suitable for a wide range of aliphatic and aromatic organics.

ION EXCHANGE

I. CONCLUSIONS AND RECOMMENDATIONS

Ion exchange is well suited for general and selective removal of heavy metals and toxic anions from dilute aqueous waste streams. The upper concentration limit for efficient operation is about 4000 mg/l. Research on the use of polymer beads impregnated with liquid ion exchange materials has some promise for extending the concentration limits.

II. PROCESS DESCRIPTION

Ion exchange involves the interchange of ions between an aqueous solution and a solid material (the "ion exchanger"). After removal of the solution, the exchanger is then exposed to a second aqueous solution of different composition which removes the ions picked up by the exchanger. The process is most frequently carried out by pumping the solutions through one or more fixed beds of exchanger.

III. APPLICATIONS TO DATE

Full-scale operations include cleanup of dilute solutions from electroplating and other metal-finishing operations, recovery of effluents from fertilizer manufacturing, and industrial deionization. Promising applications include removal of cyanides from mixed streams and use of newer exchangers for selective removal of heavy metals.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements are low, consisting primarily of electricity for pumping solutions.

The dilute purified product stream is dischargeable to sewers. The regenerant stream requires further treatment for recovery or disposal. Minor amounts of exchange materials will require disposal occasionally.

Capital costs are expected to be in the range of $200,000-$350,000, with a substantial investment in resin. Operating costs might be in the vicinity of $2-8/1000 gal.

V. OUTLOOK FOR WASTES

Ion exchange is a well developed process, which promises to be used more widely for recovery of heavy metals, and removal of both heavy metals and cyanides.

LIQUID ION EXCHANGE

I. CONCLUSIONS AND RECOMMENDATIONS

Liquid ion exchange (LIE) is a process with demonstrated potential for removal of heavy metals and hazardous anions from aqueous waste streams. It covers a much wider concentration range than conventional ion exchange. Development of new applications and reagents for waste treatment may require special economic incentives, since historically such research has been stimulated principally by high-volume hydrometallurgical applications.

II. PROCESS DESCRIPTION

Liquid ion exchange involves, first, the extraction of inorganic species (principally ionic) from an aqueous stream into an immiscible organic stream containing special reagents to facilitate the extraction, and then subsequent transfer of the species to a second aqueous stream of different composition from the feed. Process equipment is that commonly used for liquid-liquid extraction: mixer-settlers, differential columns, or centrifugal contactors.

III. APPLICATIONS TO DATE

Full-scale commercial operations include removal of molybdenum and acids from metal pickling baths, zinc from textile production effluents, and copper from various streams. Promising applications include removal of cyanides and treatment of hydroxide slimes from electroplating.

IV. ENERGY, ENVIRONMENT, ECONOMICS

The LIE process has very low energy consumption, consisting principally of electricity for pumping and mixing.

The cleaned feed stream will contain 10-50 mg/l of the organic extraction solvent. The regenerative solution into which hazardous components are stripped from the extraction solvent will require further treatment.

Capital costs depend upon the application. Values in the literature range from $10,000 (almost certainly too low) to $600,000. Total costs for treating dilute streams are estimated to be around $4/1000 gal. For concentrated stream, costs are highly variable, ranging from $0.20-$3.00/lb of metal removed.

V. OUTLOOK FOR WASTES

This method is well-developed, and particularly applicable to recovery of high-value metals from waste streams.

LIQUID-LIQUID EXTRACTION OF ORGANICS

I. CONCLUSIONS AND RECOMMENDATIONS

Liquid-liquid extraction should be considered for the recovery of organic solutes from fairly concentrated aqueous and non-aqueous solutions.

II. PROCESS DESCRIPTION

Liquid-liquid extraction is the separation of the constituents of a liquid solution by contact with another (immiscible) liquid. If the substances comprising the original solution distribute themselves differently between the two liquid phases, a certain degree of separation will result. This may be enhanced by the use of multiple contacts. A total recovery process based on liquid-liquid extraction usually requires the use of other unit processes, such as stripping or distillation for solvent and solute recovery.

III. APPLICATIONS TO DATE

Current actual or proven areas of applicability include:

1. Extraction and recovery from aqueous solution of:
    - phenol;
    - acetic acid, and other aliphatic organic acids;
    - salicylic and other hydroxy aromatic acids; and
    - oils.
2. Extraction (without recovery) of:
    - phenol from foul waters near a refinery.
3. Extraction and recovery from organic solvents of:
    - methylene chloride (from isopropyl alcohol);
    - freons (from oils and acetone, or alcohols); and
    - mixed chlorinated hydrocarbons (from acetone or alcohols).

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements are usually quite small for just the extraction step. Where solute and solvent recovery require stripping or distillation, steam requirements will be significant.

The only major environmental issues relate to (1) possible need for disposal of recovered solutes if such are not reusable, (2) the probable need for a polishing treatment on the raffinate, following extraction from water, and (3) the possible need for disposal of unwanted fractions following extraction of organic solutions.

Costs cannot be generalized usefully. However, capital investment might be in the vicinity of $1 million. Total operating costs (without credit for resource recovery) might range from well under $1/1000 gal to more than $5/1000 gal.

V. OUTLOOK FOR WASTES

The process is most attractive for treatment of concentrated, selected, and segregated waste streams where material recovery is possible and desirable. Organic solutes, of almost any nature, may be economically removed if concentrations are in the range of a few hundred ppm to a few percent from aqueous waste streams. Organic solutions containing water-soluble and non-water-soluble components may be economically separated by extraction with water.

MICROWAVE DISCHARGE

I. CONCLUSIONS AND RECOMMENDATIONS

Microwave discharge treatment of hazardous wastes is currently in the research stage. Early results are very promising.

II. PROCESS DESCRIPTION

High-frequency microwave power is used to establish a plasma or gaseous discharge in which neutral molecules are partially decomposed into metastable, atomic, free radical and ionic species. The decomposition products typically recombine to form a variety of stable molecules, some of higher molecular weight and of higher toxicity than this feed. Plasmas may be initiated in low-pressure gases of all kinds, and solids and liquids exposed to the reactive species in plasmas generally undergo chemical change. Toxic vapors and liquids introduced into an oxygen plasma undergo reactions similar to those of incineration, but at much lower temperatures.

III. APPLICATIONS TO DATE

Commercial microwave discharge instruments are used in analytical chemistry, particularly for plasma or low-temperature ashing. The only large-scale applications are for photoresist removal and plasma etching in semiconductor device fabrication. Most research has been concentrated on polymer film deposition and organic synthesis. Lockheed is currently investigating the use of microwave plasmas, particularly oxygen plasmas for the treatment of organic vapors and liquids characteristic of waste streams.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Line power requirements for microwave discharge treatment are estimated as roughly 14 kWh/lb of waste treated.

In an oxygen plasma, organic waste components are converted to products similar to those of complete combustion.

Capital costs for a 100 lb/hr facility might be in the neighborhood of $100,000. Operating costs are estimated to be on the order of $1.00/lb.

V. OUTLOOK FOR WASTES

The process should be considered for small quantities of highly toxic materials that cannot be handled by any other means, or for recovery of high-value components.

NEUTRALIZATION

I. CONCLUSIONS AND RECOMMENDATIONS

Neutralization (or more generally pH control) is a technically and economically proven process, currently in full-scale use in many industries. It has wide applicability to waste streams of diverse physical and chemical compositions, and would have to be available in almost any waste treatment facility.

II. PROCESS DESCRIPTION

Neutralization is a liquid-phase chemical reaction between an acid and a base which produces a neutral solution. It may be carried out in batch or continuous flow. It requires reaction tanks, agitators, monitoring and control capability, pumps, and ancillary equipment for handling solids and/or liquids, and storage facilities. The treated stream undergoes no change in physical form, other than solids dissolution (or precipitation) or gas evolution. The process can be used on aqueous and non-aqueous, liquids, slurries, and sludges.

III. APPLICATIONS TO DATE

The process is in full-scale use throughout many industries, e.g., pulp and paper, petroleum refining, and inorganic chemicals. It is used to treat acid exhausts, pickle liquors, plating wastes, and acid mine drainage. It can be used on almost any stream requiring pH adjustment.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements are primarily for electricity used to run pumps and stirrers. Treated streams may contain precipitated solids which require additional handling. The solids must be recovered or sent for disposal as a solid waste. There is the possibility of toxic gas being evolved, particularly if sulfides or cyanides are present in the waste stream. Capital investment requirements are highly variable, depending upon the size of the stream to be treated. Operating costs range from $0.20/1000 gal to $4/1000 gal.

V. OUTLOOK FOR WASTES

Neutralization is and will continue to be a routine and accepted part of industrial processing waste management.

OXIDATION, CHEMICAL

I. CONCLUSIONS AND RECOMMENDATIONS

Chemical oxidation and the technology for its large-scale application are well established. Oxidation-reduction, or "Redox" reactions are those in which the oxidation state of at least one reactant is raised while that of another is lowered. We recommend that chemical oxidation be considered for dilute aqueous streams containing hazardous substances or for removing residual traces of contaminants after treatment. Chemical oxidation should be considered as a first treatment step when the waste contains cyanide, when it contains constituents not amenable to other treatment methods, or as a final step to remove traces of contaminants after other treatment.

A more exhaustive study should be made of the potential for treatment of waste containing hazardous materials. Most of the literature deals only with very dilute waste streams, or with the preparation of materials from basic raw materials via chemical oxidative techniques, and little has been published relative to treatment of concentrated hazardous wastes.

II. PROCESS

The first step of the chemical oxidation process is adjustment of the pH of the solution. The oxidizing agent is added gradually and mixed thoroughly. The agent may be in the form of a gas (e.g., chlorine), a liquid (e.g., hydrogen peroxide), or a solid (e.g., potassium permanganate). Because some heat is liberated, concentrated solutions may require cooling, or may require careful measurement and handling to avoid violent reactions.

III. APPLICATIONS TO DATE

Application to industrial wastes is well developed for cyanides and for phenols, organic sulfur compounds, etc., in dilute waste streams. The primary application has been in converting and destroying cyanides from plating and metal finishing operations.

The chlor-alkali industry uses chemical oxidative techniques to remove mercury from ores, as well as from cell wastes. Mercury removal rates of over 99% are claimed for concentrated ores, and residual mercury levels of less than 0.1 ppm for chlor-alkali sludge.

The technique is also used to remove organic residues from drinking water, or to remove residual chlorine after chlorine treatment. Gases have been treated by scrubbing with oxidizing solutions to destroy odorous substances. Chemical oxidation is also used for odor destruction in the manufacture of kraft paper and in the rendering industry.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Total energy consumption is low; the only requirements are for pumping and mixing.

A disadvantage of chemical oxidation for waste treatment is that it introduces new metal ions into the effluent that might require further treatment. The only waste that appears troublesome is the sludge that can develop in the oxidation treatment of cyanides when iron and some other ions are present. A facility for chemical oxidation of 10^3 gpd of highly concentrated cyanide waste from a plating operation, using batch alkaline chlorination would require a capital investment of $100,000. Fixed costs would be $18,300 annually and variable costs $36,700, giving a unit cost of $229.20/$10^3$ gal. For a less highly concentrated waste (100 ppm copper cyanide and 100 ppm sodium cyanide), the operating cost would be about $170/$10^3$ gal. Costs could be lowered if the daily flow rate were to increase and the treatment operation could be continuous rather than batch.

V. OUTLOOK FOR WASTES

In addition to the already-established applications for removal of hazardous substances, chemical oxidation may be used to remove chlorinated hydrocarbons and pesticides from dilute streams. Laboratory and pilot studies have demonstrated the potential for this application.

The extent to which the technique can be used to remove hazardous substances from industrial sludges may be limited because of inefficiency and incompleteness of the reaction.

The use of chemical oxidation for concentrated wastes should have careful evaluation for reasons of economics, process safety, and the addition of chemicals that may add to the pollutant load.

OZONATION

I. CONCLUSIONS AND RECOMMENDATIONS

Technology for large-scale ozone application is well developed. Feasibility has been demonstrated for treatment of cyanides and phenols, and laboratory and pilot studies indicate potential for chlorinated hydrocarbons, polynuclear aromatics, and pesticides.

We recommend that ozonation be considered for treatment of aqueous or gaseous waste streams containing less than 1% oxidizable hazardous components and as a preliminary treatment for more concentrated wastes not amenable to other techniques. We also recommend ozonation as a final treatment process where more complete removal of oxidizable substances is required.

A more exhaustive study should be made of the literature on the susceptibility of various compounds to ozonation. Laboratory studies are needed to evaluate the effectiveness of treatment of pollutants of current concern. Additional research and development aimed at more efficient ozone generation and ozone/water mixing should be supported.

II. PROCESS

Since ozone is a powerful oxidizing agent and an extremely reactive gas that cannot be shipped or stored, it must be generated on site immediately prior to use. Ozone generated at a concentration of <2% and a pressure of <15 psi from a stream of air or oxygen previously dried to a dewpoint of -50°C or lower is introduced into a contact chamber designed to ensure good mixing with the waste stream. For aqueous wastes, a venturi injector, a porous diffuser, or an impeller is used to mix ozone and liquid at high velocity for 10 minutes or more. Liquid depth is at least 15 feet, and two or more reactors are frequently employed. For gaseous waste streams, a porous diffuser is used if ozonized air is generated at positive pressure; at atmospheric pressure, a wet scrubbing process is used, with a fine mist of ozone-saturated water sprayed into a contact chamber. Contact times for gaseous streams is 5-60 seconds.

III. APPLICATIONS TO DATE

Ozone, besides being a powerful reducing agent, has antibacterial and antiviral properties. This disinfecting power has been responsible for most large-scale applications. The process is widely used in Europe to purify and improve drinking water, and there have been a number of installations in the United States for treatment of municipal sewage plant effluents. It has also been used to remove sulfide and other odors from rendering plant effluent; fermentation odors from a pharmaceutical plant; treatment of liquid effluent containing cyanides, sulfides, sulfites and other hazardous components after biological treatment; reduce cyanide levels from effluent of a tire plant, a chemical plant, and an electroplating facility. In combination with activated carbon adsorption, ozonation has been used to remove color from waste dyeing water. Oxidation of phenols in coke oven wastes, wood products waste and biologically treated refinery waste.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Ozonation can be expensive, but may be economically competitive for treatment of dilute waste streams. Generation of ozone is the dominant cost component in terms of capital and power. With air feed, energy requirements are from 7.2 to 9.0 kWh/lb of ozone generated. Power requirements are half this figure if oxygen is used for feed. Any improvement in ozone demand or efficiency would improve economics; the catalytic effect of UV light can extend the effect of ozonation dramatically and can reduce ozone demand by a factor of two. Labor and space requirements are low.

Concentrations of ozone leaving the contact chamber are carefully monitored; sometimes the ozonized air is cycled to provide pretreatment of incoming aqueous waste. The waste stream effluent is also monitored, and the dosage increased if necessary. Gaseous effluent is discharged directly to the atmosphere; aqueous effluent may be discharged to a sewer or natural body of water where the oxygen-rich water is beneficial.

V. OUTLOOK FOR WASTES

Complete oxidation to CO_2 can sometimes be achieved; in other cases, oxidized intermediates may be formed that resist further ozonation. Whether a given degree of oxidation constitutes satisfactory treatment depends on the criteria for the particular waste stream or disposal site. Slurries, tars, sludges and solutions in oxidizable liquids are generally not suitable for ozonation. Although ozone itself is a toxic substance, the risk of exposure to toxic levels is small.

PHOTOLYSIS

I. CONCLUSIONS AND RECOMMENDATIONS

Technology for large-scale application of photolysis to wastes is not highly developed. Further laboratory studies of photolysis of selected candidate waste streams (for example, pesticide contaminated solvents) should be conducted. Pure photolysis is not likely to be a practical industrial waste treatment process within the next 5-10 years, but UV-assisted ozonation and chlorination are promising in the near term.

II. PROCESS DESCRIPTION

In photolysis, chemical bonds are broken under the influence of UV or visible light. Products of photodegradation vary according to the matrix in which the process occurs, but the complete conversion of an organic contaminant to CO_2, H_2O, etc., is not probable. Equipment required includes a source of UV/visible radiation, such as a mercury arc. Reactor geometry and materials of construction must allow adequate penetration of the light into the waste.

III. APPLICATIONS TO DATE

Pure photolysis has been investigated only in laboratory-scale studies. Combined UV/ozonolysis and UV/chlorination have been used in pilot and full-scale applications in the hazardous waste area.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Any photolysis process is relatively energy-intensive. There are not sufficient data to allow estimation of either process economics or environmental issues. In general, the process effluent is a stream with physical characteristics similar to those of the input stream, but with different chemical characteristics. Organic hazardous components are not completely degraded and the residues may still pose hazard.

V. OUTLOOK FOR WASTES

Applications are probably highly specialized, detoxification of pesticide-contaminated solvents is one possibility. However, pure photolysis requires research and testing at laboratory and pilot-scale to demonstrate applicability to hazardous waste.

REDUCTION, CHEMICAL

I. CONCLUSIONS AND RECOMMENDATIONS

Reduction reactions are among the most common chemical processes; reduction-oxidation or "Redox" reactions are those in which the oxidation state of at least one substance is raised while another is lowered. The technology for large-scale reduction of some industrial wastes, sometimes allowing recovery of metals, is well developed. We believe that the process could well be adapted to remove hazardous substances from dilute wastes, to pretreat wastes that have constituents not amenable to other methods, and to remove traces of contaminants.

II. PROCESS

The equipment for reduction processes is simple: only storage, metering, mixing, pumping and instrumentation, with the major cost for reducing chemicals. The economics vary with the substance being treated. Introduction of foreign ions into the stream is a real or potential disadvantage; otherwise it is straightforward.

III. APPLICATIONS TO DATE

The application to industrial wastes is already well established for dilute waste streams, especially those containing chromium (VI), and other hazardous substances, such as lead and mercury. In addition to detoxifying hazardous substances, the process sometimes allows recovery of metals. The plating and tanning industries use the process to reduce highly toxic chromium (VI), to chromium (III), which is less hazardous and can be precipitated for removal.

The process also finds application in the chlor-alkali industry for removal of mercury from effluents. It appears to have potential for removing other hazardous substances, e.g., cadmium and antimony, in diluted streams.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Total energy consumption is low; the only requirements are for pumping and mixing.

A disadvantage of chemical reduction for waste treatment is that it may introduce new ions into the effluent that might necessitate further treatment. Air emissions are not significant. There may be problems with land disposal or residues, especially those susceptible to acid leaking. A facility for chemical reduction of 2,000 gpd of chromium (VI) waste from a plating operating, using batch sulfur dioxide treatment would require a capital investment of $230,000. Variable operating costs would be $51,400 and fixed costs $41,600 annually. Unit costs would be $\$193.80/10^3$ gal. Costs could be lowered if the daily flow rate were to increase and the treatment operation could be continuous rather than batch.

V. OUTLOOK FOR WASTES

We believe there should be a more exhaustive study of the potential for reduction processes for concentrated hazardous wastes. It should certainly be considered as a treatment step whenever chromium VI is a constituent of the effluent. It may be a method for treating wastes that have constituents not amenable to other treatment, and as a final polishing step for removing traces of contaminants.

REVERSE OSMOSIS

I. CONCLUSIONS AND RECOMMENDATIONS

Reverse osmosis (RO) should be considered for treatment of aqueous waste streams containing organic and inorganic species in solution. Total dissolved solids in the feed stream may be as high as 34,000 ppm.

II. PROCESS DESCRIPTION

The heart of the reverse osmosis process is a semipermeable membrane which is permeable to solvent, but impermeable to most dissolved species, both organic and inorganic. Separation is brought about by means of an applied pressure gradient. To protect the membranes for chemical attack and plugging, oxidants, iron and manganese salts, and oils and greases are generally removed prior to application of RO.

III. APPLICATIONS TO DATE

There are about 300 full-scale plants worldwide using reverse osmosis for desalination of sea or brackish water. Reverse osmosis has been used very successfully in the treatment of electroplating rinse waters, not only to meet effluent discharge standards, but also to recover concentrated metal solutions for reuse. A limited number of other full-scale uses can be found in the treatment of sulfite streams from the paper industry and in food processing.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Energy requirements are of the order of 10 kWh/1000 gal of product water.

The concentrated brine or solute solution presents a problem for disposal, if not recoverable.

Capital costs range from about $0.50-4/gpd of purified water output, depending on the volume of waste to be treated. Total operating costs are in the range of $1-5/1000 gal.

V. OUTLOOK FOR WASTES

Use of RO for industrial waste treatment is growing rapidly. The process is particularly useful for concentrating waste streams containing dissolved organics or inorganics, to facilitate recovery, or to reduce volume.

STEAM DISTILLATION

I. CONCLUSIONS AND RECOMMENDATIONS

Steam distillation is a proven process for removing water-immiscible, volatile compounds from process or waste streams. It can be applied to any stream that can be contacted with steam or water without reaction or decomposition. It can be used with liquids, slurries, sludges, and solids.

II. PROCESS

Steam distillation takes advantage of the unique vapor pressure relationship of two immiscible liquids. The additive vapor pressures allow distillation at lower temperatures. It is usually conducted as a batch operation: the still is charged, the charge is heated to temperature, and the distillation conducted by bubbling steam through the liquid phase. In semi-batch operation, the charge containing a high ratio of volatiles to non-volatiles is fed to the still continuously for a given period while the volatile component is steam-distilled from the mixture.

III. APPLICATIONS TO DATE

The widest application is in the petroleum industry where steam and feedstock are introduced into a multi-tray distillation column to produce gasoline, lube oil, or naphtha. Without the use of steam or steam and vacuum together, the high distillation temperature would result in decomposition. The process is also used for removing low boiling components from a mixture. In the soap industry, glycerine is recovered from spent soap lye; in the naval stores industry turpentine and gum rosin are recovered from pine gum; fatty acids and tall oil rosin are obtained from crude tall oil, a by-product of sulfate wood pulp production. A solvent extraction process removes organics from paper before the wood fiber can be reused; through steam distillation the solvent is recovered. In the production of coke from coal, quantities of aromatic hydrocarbons are also produced. The wash oils from the ovens are steam stripped to recover the aromatic hydrocarbons.

IV. ENERGY, ENVIRONMENT, ECONOMICS

The major energy requirement is for steam. In one application, the steam requirement would total 29,200 lb per 3,000 gal of treated degreasing waste, or per 1,000 gal recovered perchlorethylene. Power requirements would be 30 kWh per 3,000 gal waste.

The wastewater from condensed steam in the steam distillation process will contain traces of volatile organics, and may have to be steam-stripped before disposal.

The fixed capital investment (new equipment) for a steam distillation unit with a capacity of 3,000 gal/week degreasing solvent would be about $130,000. Operating costs would be $1,424. Credits for perchlorethylene at $2/gal and $0.05/gal for the oil/grease mixture used for boiler fuel would more than offset treatment cost.

V. OUTLOOK FOR WASTES

Numerous industrial wastes are treated by contract disposal companies using steam distillation to recover valuable components or reduce waste volumes. With the increase in value of hydrocarbon solvents and increasingly strict regulations regarding landfill with sludges containing these solvents, the use of steam distillation is expected to increase.

STRIPPING, AIR

I. CONCLUSIONS AND RECOMMENDATIONS

Air stripping of ammonia from biologically treated domestic wastewater is being developed as a means of reducing nitrogen content before discharge. It is suitable only for dilute solutions, since the emission level of ammonia from a concentrated solution would be too high. Furthermore, steam stripping would permit recovery of the ammonia from more concentrated solutions. Application of air stripping to other gaseous compounds would depend on the environmental impact of the resulting emissions.

II. PROCESS

Holding ponds, with or without surface agitation, and spray ponds have been investigated, but the packed tower appears to be the most compact and efficient means of air stripping. Removal efficiencies of over 90% have been obtained in pilot tests with wastewater containing 60 ppm nitrogen. The wastewater containing ammonia and a lime slurry (lime added for phosphate removal) are fed to a rapid mix tank, and thence to a settling basin, where the calcium phosphate and calcium carbonate settle out. The clarified wastewater is pumped to the top of two towers packed with a series of horizontal pipes. Air is drawn up through the tower against the falling wastewater by large fans. After the ammonia is removed, the wastewater flows into the recarbonation basin where compressed carbon dioxide-rich gas from the lime recalcining furnace is bubbled through to precipitate and recover calcium carbonate, for calcination and recycle of lime to the system.

III. APPLICATIONS TO DATE

Full-scale packed towers have been used at two locations in California for treating domestic wastewater.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Electric power requirements for treating 15 million gpd are in the range from 1600 to 1800 kWh/hr. The recalciner requires about 8 million Btu (8000 ft^3) natural gas/ton of feed, or 192 million Btu/day.

When the ammonia concentration is about 23 ppm and the air-to-water ratio is 500 ft^3/gal, the concentrated ammonia in the saturated air leaving the tower is about 6 mg/m^3, well below the odor threshold. Disposal of about 25 tons/day of sludge requires a significant amount of land, but does not pose an environmental hazard.

The capital investment would be about $7.8 million; fixed costs would be $1,420,000, and variable operating costs would be $940,000/year.

V. OUTLOOK FOR WASTES

It is unlikely that many other applications of air stripping will be found.

STRIPPING, STEAM

I. CONCLUSIONS AND RECOMMENDATIONS

Steam stripping should be considered whenever it is desirable to remove volatile components (e.g., organics, H_2S, NH_3) from aqueous waste streams.

II. PROCESS DESCRIPTION

Steam stripping may be considered a form of fractional distillation. Live steam is injected into the bottom of the distillation column, and carries dilute volatile components with it. There are two aqueous output streams, one a concentrated solution of the volatile organics and the other a dilute stream containing only residual traces of volatile organics.

III. APPLICATIONS TO DATE

Steam stripping has been used for many years to recover ammonia from coke oven gas. It is also used to recover sulfur as H_2S from refinery raw waste. Other applications include phenol recovery, vinyl chloride monomer removal from PVC suspension resins, and removal of organics and sulfur from Kraft mill condensates. Research work is in progress for steam stripping of light chlorinated hydrocarbons from industrial waste water.

IV. ENERGY, ENVIRONMENT, ECONOMICS

The primary energy requirements are for steam. Between 0.5 and 2.5 pounds of steam are required per gallon of waste water. The concentrated stream containing the bulk of the volatile organic components is processed for recovery or incinerated. If the incinerated stream contains sulfur, emission of SO_2 must be considered. The impact of discharging the treated dilute stream depends on the nature and residual concentration of the volatile organics of the waste water.

Capital investment for a new 200-gpm, single-stage (one column) "sour water" steam stripper would be between $500,000 for mild steel and $850,000 for stainless-steel construction. Treatment cost by this system would be about $10/1000 gal. A capital investment closer to $1,700,000, would be required for a two-stage, two-column, 200-gpm system that would recover NH_3 and H_2S for credits.

V. OUTLOOK FOR WASTES

The use of steam stripping for industrial waste treatment is growing. The most attractive applications are those that permit byproduct recovery, thus to offset fairly high operating costs. The process is energy-intensive, with steam costs amounting to close to 80% of operating costs.

ULTRAFILTRATION

I. CONCLUSIONS AND RECOMMENDATIONS

Ultrafiltration is a membrane filtration process that separates high molecular weight solutes or colloids from their surrounding media. The process has been successfully applied to both homogeneous solutions and to colloidal suspensions that are difficult to separate by other techniques. Commercial use has been focused on aqueous solutions.

Retained solute or particle size is one characteristic distinguishing ultrafiltration from other filtration processes. It filters out particles as small as 10^{-3} to 10^{-2} microns. Where solutes are being separated from solution, the process can serve as a concentration or fractionation process for single-phase streams. It competes with adsorptive and evaporative processes, and has the potential for broader applicability than conventional filtration. Usually the concentrate requires further processing if a pure solute is to be recovered.

II. PROCESS

Ultrafiltration membranes have an extremely thin selective layer supported on a thicker spongy substructure, and it is possible to tailor membranes with a wide range of selective properties. A solution containing molecules too small to be retained by the membrane and larger molecules that will be 100% retained is passed in a pressurized stream. The larger molecules are collected from the upstream side and the smaller molecules downstream.

III. APPLICATIONS TO DATE

Ultrafiltration is used for electrocoat paint rejuvenation and rinse water recovery, protein recovery from cheese whey, and metal machining oil emulsion treatment, with capacity to handle approximately 100 million gallons per year for each application. There are also smaller (on the order of 10 million gpy) plants for treatment of textile sizing waste and wash water from electronics component manufacturing, and for production of sterile water for pharmaceutical manufacturing.

IV. ENERGY, ENVIRONMENT, ECONOMICS

Electrical energy for pumping to maintain flow at operating pressures may be as much as 30% of total direct operating costs.

Ultrafiltration residues are typically a concentrate of the undesirable or hazardous components and usually require further processing unless valuable by-products can be recovered.

Capital and operating costs are dependent on the specific application and the capacity of the system. For large plants, capital costs may be $1-$4/gpd; operating costs may be $5-$10 per 10^3 gal. Coupled with the economies of reuse of salvaged materials, these costs are often acceptable.

V. OUTLOOK FOR WASTES

There are a number of other applications where ultrafiltration may become commercial within the next five years. These include: treatment of dye waste, pulp-mill waste, industrial laundry waste, and recovery of sugar from orange-juice pulp, protein from soy whey, products from pharmaceutical and fermentation industries, and purification of power-plant boiler feedwater and water for beverages.

Application to hazardous wastes is already well advanced, since many of the aqueous solutions treated present severe sewage problems.